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THE USE OF THE MAURER FACTOR FOR ESTIMATING THE COST OF A TURBINE ENGINE IN THE EARLY STAGES OF DEVELOPMENT

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Military managers are faced with increasing systems costs. One area where this increasing cost is especially true is in the acquisition of aircraft weapons systems. A driving factor in the aircraft cost is the turbine engine, and therefore acquisition managers have been tasked with developing cost estimating methods that will more accurately predict turbine engine cost. At present, several parametric costing models available are briefly discussed in this report. However, the primary objective of this report, is to evaluate a costing technique used extensively by the Navy--the Maurer Factor (MF) technique. The MF technique is a parametric costing technique based on the materials in a turbine engine. The report includes the following: (a) a detailed description of the MF technique; (b) a validation of the MF technique; (c) the development of an estimated MF (EMF) model using engine performance parameters; and (d) statistical analysis and validation of the EMF models.

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THE USE OF THE MAURER FACTOR FOR ESTIMATING THE COST OF A TURBINE ENGINE IN THE EARLY STAGES OF DEVELOPMENT

A Thesis

Presented to the Faculty of the School of Systems and Logistics

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Logistics Management

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INTRODUCTION

Background

Today's military managers are faced with increasing systems costs. Because of these increasing costs, managers must insure that every defense dollar is spent in the most efficient way possible.

> DOD is engaged in an effort to reduce its hardware costs. While the military's defense costs are escalating, its responsibility to a sustained national security persists. It is therefore DOD's desire to re-evaluate existing acquisition procedures and find new ones in its drive to procure the best hardware value [18:1].

One area where this increasing cost is especially true is in the acquisition of aircraft weapons systems. A driving factor in the aircraft cost is the turbine engine, and therefore acquisition managers have been tasked with developing cost estimating methods that will more accurately predict engine cost. At present there are several cost estimation models which can be used in the different phases of the acquisition process. The primary area of interest in this study will be cost estimation of turbine engines which are in the early development stage.

Problem Statement

The Propulsion Branch, Turbine Engine Division, Air Force Aero Propulsion Laboratory (AFAPL/TBP) Wright-

Patterson AFB, Ohio needs a model which can be used to estimate the cost of the turbine engine early in its development stage.

Justification

The Turbine Engine Division is one of four divisions within the AFAPL. Its mission is the development of advanced engines for possible use in future weapons systems. Within the Turbine Engine Division there are four branches: (1) the Performance Branch, which conducts basic engine research, (2) the Components Branch, which conducts exploratory research--working mainly with improvement of engine components, (3) the Propulsion Branch, which works in advanced engine development, and (4) the Engine Development Branch, which matches advanced engines developed in the Propulsion Branch to a specific mission need. The Propulsion Branch uses components developed by the Components Branch to design actual engines. Some of these engines are built and tested while others remain only concepts on paper. Although these engines could be used in future weapons systems, normally they are not. Instead, when the requirements for a weapon system are identified, the technology learned in Propulsion Branch engines, and possibly even components of the engines, are used to develop an operational engine to be used in the weapon system (17).

The research topic was generated by the Propulsion Branch of the Turbine Engine Division. Since the possibility

does exist that the complete engines or improved components developed by the Propulsion Branch will be used by some Air Force agency in the acquisition of a new weapon system, the Propulsion Branch must be able to accurately predict the cost of these advanced engines (17).

The accurate estimation of engine costs in the early development stages is necessary today in view of the increased emphasis on tighter defense budgets. This increased interest in cost estimation was illustrated by the following statement in OMB Circular No. A-109:

> Maintain a capability to: Estimate . . . costs for system development, engineering, design, demonstration, test, production, operation and support. . . . Estimate . . . cost during system design concept evaluation . . . to ensure appropriate tradeoffs among investment costs, ownership costs, schedules, and performance [6:5].

If the Air Force is to maintain its combat readiness despite scarce money resources, then it must be able to accurately predict the spiraling costs of its new weapon systems. Since a decrease in these costs is nowhere in sight, the Air Force must be able to anticipate and plan for the rising costs in its acquisition of new weapon systems (18:3-6).

One of the major cost driving factors of a weapon system is the turbine engine, which has not been exempt from the problem of rising costs. There are many reasons for the increasing cost of today's engines. Growing inflation is one, but the increased performance requirements of today's advanced technology engines have also had a great effect on cost. Such requirements as improved thrust to weight ratios,

improved fuel efficiency, and less noise and air pollution have been met, but the result has been increasing cost. For example, to obtain the thrust required in high technology engines, one of the trade-offs has been a drastic rise in turbine inlet temperatures. Techniques were developed to compensate for these higher temperatures. One such technique was turbine air cooling. Air cooling is accomplished by forcing air through passageways drilled in the turbine blade (22:69-73).

Another procedure for coping with the hotter temperatures has been through the development of exotic super-alloys. Through the use of these metals, engine designers have developed blades that can sustain temperatures up to 2100° F.

The performance results of these turbine sections have been good, but the cost is high. For example, the price of an advanced technology turbine disk ranges from $25,000 to $30,000 (12:81-82). The reasons for the high prices are the expensive machining techniques and the increase in cost of metals. According to Aviation Week, the commodity price of some basic metals used in the aircraft industry has risen by 125 percent since 1960 (28:73-77). Scientists are looking at ways to reduce these costs, such as the development of cheaper composite materials, but it is still apparent that acquisition managers will be faced with the problem of expensive engines

in the future. Cost estimation is one tool that could be used to help manage rising costs.

Several cost estimation models exist; however, only one of these models was specifically designed for use on the types of engines of primary interest to the Propulsion Branch. The results of previous studies have indicated that some of these models are more accurate than others. When dealing with expensive engines, however, small errors in cost estimation models can lead to disastrous results.

For example, one of the models available was developed by the Rand Corporation. Research was conducted using this model to estimate the cost of the F100 turbine engine. The estimated cost of the engine using the Rand model was $675,359 in fiscal year (FY) 1970 dollars. The actual FY76 cost of the engine was $2,000,000 which equates to $1,148,000 in FY70 dollars (18:5). Since Propulsion Branch analysts desire an estimated value within 25 percent of the actual cost, this underestimation of $472,641 is unacceptable. Therefore, further research is required to determine which of the existing models are most appropriate for the needs of the Propulsion Branch (17).

Chapter 2

LITERATURE REVIEW

Cost Estimation

> Estimating is the process of reckoning in dollars the sum necessary to manufacture a product at some future time by calculating and projecting the future costs of men, materials, methods, and management. It is a part of every business. The production of any item is tied to estimating from the time it is considered feasible, through development and engineering, until the cost of every nut, bolt, and screw can be priced as a part of the total cost for the job [8:1].

Military service manuals on cost estimation listed as many as five different methods; other sources listed many other variations such as synthesis, analysis, roundtable estimating, estimating by comparison, detailed estimating, analytical appraisal, comparative analysis, and statistical analysis (2:2). These methods can be placed in two categories--engineering-accounting and statistical (1:2).

Engineering-accounting. The engineering accounting approach, also referred to as the industrial engineering approach, the grass roots approach, the building block approach, or the bottom up approach,

> . . . entails the examination of separate items of work at a low level of the work break down structure with detailed estimates developed for the functional costs of engineering, manufacturing, quality control, etc. In turn, these are broken down by labor, material, and other elements of cost for each item [1:3].

The summation of these individual costs is used to compute the total system cost (17). According to a Rand report:

> Engineering estimating procedures require considerably more personnel and data than are likely to be available to government agencies under any foreseeable conditions [2:5].

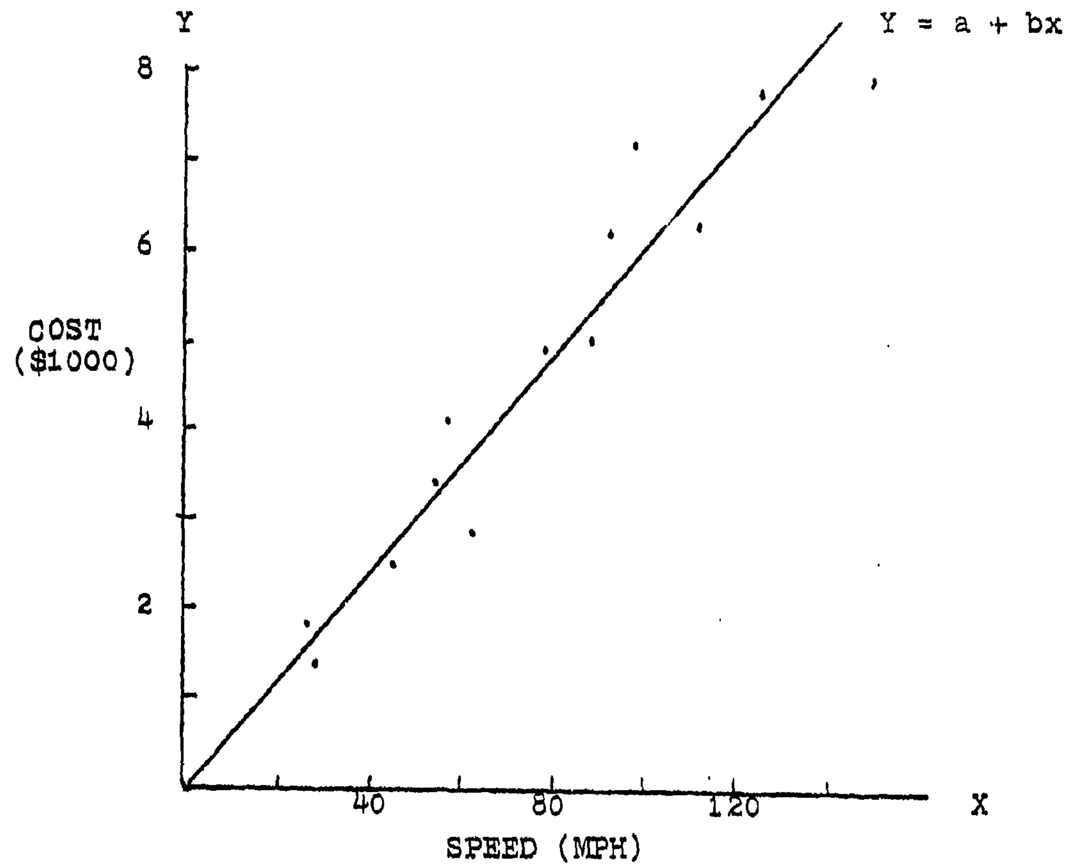
Nevertheless, the engineering method is sometimes used in the later phases of the acquisition process when more detailed information is known. One advantage of the engineering method is increased accuracy because of the detail required in arriving at the final cost. However, it is also the most expensive and time consuming. Many people are required to analyze a system's components and determine the price of each (2:2-8). Since the engineering accounting approach entails more resources than the statistical method, the latter is the most widely used in cost estimation.

Statistical analysis. The use of statistical analysis in cost estimation has proven to be one of the more practical methods. The key to this methodology is the extensive use of historical data pertinent to the system being studied. Pertinent historical data may be defined as characteristics of previous systems which are similar to characteristics of the system under consideration (2:13-16). Statistical methods are used to analyze data and establish cost driving relationships between the old and new system (15:1-2). For example, it might be determined from analyzing historical data in the automobile manufacturing

industry that when the speed capability of a new model automobile increased by a certain amount, the price also increased by a proportional amount. By using the relationship of speed to price, general equations can be developed to estimate the price of any new car. This simplified example demonstrates one of the basic concepts used in statistical cost estimation--linear regression (29:315-326).

Linear regression. Linear regression is a method commonly used in cost estimation to analyze historical data. One characteristic of the system, for example the speed of a car versus cost, is chosen, and all the data collected concerning cost versus speed are plotted on a two dimensional graph. The independent variable speed is plotted on the horizontal axis (x) against the dependent variable cost on the vertical axis (y). Once the speed/cost data are plotted, a line is fitted through the plotted data points. By determining the slope of the line, the x-axis intercept, and the y-axis intercept, a linear equation describing this line can be formulated. This general equation can then be used to estimate the price of any car based on the desired speed capability of the car (Figure 1). Detailed procedures for fitting a line can be found in basic statistics texts (30:368-395).

A problem that must be considered when using regression analysis is the significance of the derived



a = y-axis intercept

b = slope of line

x = value of independent variable

Figure 1

Graphic Representation of Simple Linear Regression

equation. One method of testing for a significant relationship between x and y is called the t-ratio or ratio of a coefficient to its standard error. The procedure develops a hypothesis that x and y are not related, and then testing of the data is performed to determine if the null hypothesis can be rejected (29:341-347). (See Appendix D for further explanation of regression analysis.)

Turbine Engine Cost Estimation

The statistical methods previously discussed were the primary methods used in developing turbine engine cost estimation models for Air Force use (2:v). When developing an engine cost estimating model using linear regression techniques, engine parameters must be selected which will have an effect on production cost. This relationship, between cost and parameters, is called a Cost Estimating Relationship (CER), and the method is termed Parametric Costing (2:79-87). For turbine engines these CERs include such parameters as thrust, weight, maximum RPM, turbine inlet temperature, cruise mach, and specific fuel consumption (20:v). Historical data concerning engine parameters are collected, and linear regression is used to determine which parameters show the greatest relationship to production cost. In the regression model, the engine parameters are the independent variables and production cost is the dependent variable. From the regression analysis, generalized

equations are developed which can be used to estimate the cost of the engine (2:33-50).

Rand model. The Rand Corporation has conducted extensive research in the cost estimation area. The majority of its work deals with parametric costing techniques. Rand's latest effort using parametric costing was an analysis of turbine engine life cycle costs. Of particular interest to this research effort was the portion of the Rand study dealing with engine production cost estimation.

As with most other cost estimation models, the Rand model used several CERs in its equations. Rand studied many different engine parameters and determined that parameters such as thrust, weight, turbine inlet temperature, and specific fuel consumption were the primary cost drivers in engine production cost (19:13). However, at this point, Rand varied from the standard technique of showing a direct relationship between an engine parameter, such as thrust, and cost. Instead, Rand introduced a level of technology factor in its model. Rand believed that if an engine pushes the state-of-the-art, the result would be an increase in cost, and this factor should be part of the cost estimating equation (19:13).

In using the state-of-the-art factor in the model, Rand introduced two terms which are not used in other cost

estimating models. These terms are time of arrival (TOA) and model qualification test (MQT). TOA is the time designated that an engine passes MQT, and is ready for full production (20:5). Rand defined MQT as

> . . . the final military qualification, normally 150 hours, after which the engine is considered to be sufficiently developed for installation in a production aircraft [27:8].

Rand used a separate regression model containing the previously described engine parameters to calculate TOA. This TOA was given in quarters of a year with October 1942 used as the base year. The calculated TOA was compared to the engine actual TOA, and the difference of the two was the engine's delta TOA (ΔTOA). The ΔTOA is the state-of-the-art factor which is used in the CER to calculate the estimated production cost.

For example, assume that a new engine is being developed, and the values required for the cost estimation model are known. The calculated TOA is determined from the computation of the known values in the equation. If this TOA is higher than the engine's actual TOA, the state-of-the-art required to build this engine is being pushed, and the result will be increased cost. Table 1 is a listing of the equations for the Rand model (20:3-19).

Rand's first report on this type of cost estimation model was in 1974. A research effort conducted by Captains Rodney J. Mullineaux and Michael A. Yanke reported the results of the model using data they had collected on the

Table 1

Rand Model (19:25)

State-of-the-Art Trend:

$$TOA26 = -856.38 + 110.10 \ln TEMP + 11.41 \ln TOTPRS$$
$$-26.08 \ln WGT - 16.20 \ln SFCMIL + 18.37 \ln THRMAX$$

1000th Unit Cost:

$$\ln KPUSP = -82070 + .70532 \ln THRMAX + .00674\ TOA26$$
$$+.4571 \ln MACH + .01804\ \Delta TOA26$$

Terms: (13:xvii-xviii)

KPUSP	=	Production cost of 1000th engine
MACH	=	Maximum envelope Mach number
SFCMIL	=	Specific fuel consumption at military thrust, sea level static, lb/hr/lb thrust
TEMP	=	Maximum turbine inlet temperature
THRMAX	=	Maximum thrust (with after burner if after burning configuration)
TOA26	=	Time-of-arrival index in quarters
ΔTOA26	=	TOA26 minus MQT (150 hrs) calender quarters
TOTPRS	=	Pressure term (product of QMAX & pressure ratio), lb/ft^2
WGT	=	Weight of engine

F100 engine. As indicated earlier, the estimated cost of this engine using the Rand model was $472,641 below the actual engine cost--an error of 70% (18:5).

In 1977 Rand issued another report in which the data base used to construct the original cost estimation model had been updated, thus leading to improvements in the model. The model shown in Table 1 is based on this 1977 report. Currently, no formal study of the new model has been conducted, although a cost analyst who has been working with this model indicated that the estimated costs are again below the actual engine costs.

Although the Rand model could be used by the Propulsion Branch, the model design makes it more appropriate for use in earlier development stages where less detail about an engine is known (17).

Grumman model. The Grumman model is another cost estimation model which was based on the Rand concept just discussed. The Grumman engine production cost model was part of a Life Cycle Cost Model developed by the Grumman Aerospace Corporation for the Air Force Flight Dynamics Laboratory at Wright-Patterson AFB, Ohio. It was designed to predict the total cost of an advanced aircraft system including research, development, testing, and engineering; production; initial support; and operations and support costs. A portion of the model deals specifically with the prediction of engine costs (11:1)

As in the Rand model, the Grumman model relates cost to design parameters and vehicle performance requirements. Grumman's data base was developed using Rand's cost estimation data base and industry sources. The cost data from these sources were combined with the appropriate engine design parameters and regressed to produce CERs, as explained earlier (11:19). This model also relates the production costs to advances in engine technology. Therefore, as in the Rand model, a TOA exists in the Grumman model, but instead of TOA Grumman used the term Delta Technology Time (DTT) (11:66).

This model was designed to be used with a complete weapon system; thus, the Propulsion Laboratory and other departments within AFAPL have not used this model and are not aware of its value or credibility at this time. At present, the model is being tested on new engines to evaluate its practicability in cost estimation of advanced engines (17). (See Table 2 for the Grumman Model.)

Mullineaux and Yanke model. In June 1976 Captains Mullineaux and Yanke of the Air Force Institute of Technology, Wright-Patterson AFB, Ohio, conducted a study to build a model for AFAPL for estimating engine costs. This study led to the development of a new model, Model 8 in their thesis. This methodology was built upon the CERs developed by Rand with a few modifications--the addition of material factors developed by the Navy, to be discussed

Table 2

Grumman Model (11:85)

State-of-the-Art Trend:

$$\text{DTT} = 8.86 \ln \text{ENGTWR} + 34.56 \ln \text{TIT} - 218.7$$

1000th Unit Cost:

$$\text{Engine \$million} = 8.880 \times 10^{-6} (1.048)^{\text{DTT}} \left(\frac{\text{TOTHRST}}{\text{NOENG}}\right)^{.527} (\text{PRESS})^{.555}$$

$$\text{Press} = 2116 \left[\text{EPR} + .7\ \text{EPR} * \text{SLMACH}^2 - 1\right]$$

Terms:

DTT	=	Delta technology time
ENGTWR	=	Engine Thrust-To-Weight Ratio
EPR	=	Engine sea level static maximum pressure ratio
MQT	=	Model Qualification Test (MQT = 150 hr Qualification test year minus 1900)
NOENG	=	Number of Engines
PRESS	=	" . . . engine internal pressure which is a measure of complexity affecting the number of stages and number of parts [7:85]."
SLMACH	=	Maximum Engine Design Mach Number
TIT	=	Turbine Inlet Temperature
TOTHRST	=	Maximum Engine Thrust

later in the Maurer Factor (MF) approach. Mullineaux and Yanke felt that the inclusion of a material factor within their model " . . . would automatically update the cost-estimating model as changes in technology occurred [18:21]."

Their final report recommended Model 8. The findings indicated a ninety-five percent certainty of estimating the actual cost within $375,000. Although Model 8 did not include a material factor, as depicted in Table 3, the variables within the model did allow for engine design change. Models 3, 4, and 6 did present rationale that material factors were powerful cost estimating parameters. However, Model 8 achieved a lower percentage of error than those dealing with both performance and material parameters (18:80-81). Table 4 lists Models 3, 4, and 6. Furthermore, Mullineaux and Yanke assumed that the learning curve did not apply to turbine engine production cost. Therefore, their model's production cost was based on the average cost of all engines of a particular type produced.

Cost analysts working with turbine engines believe that the learning curve theory does apply; therefore, as the number of engines produced changes, the cost will change. Using the cost obtained from the Mullineaux and Yanke models, a compensation in cost change due to change in production quantity cannot be made (17).

Maurer factor. A cost estimation model that might be more appropriate for Propulsion Branch use is one which

Table 3

Model 8 (18:56)

$$COST = -1773919.3 + 690.1\,(TIT) + 1052.9\,(AF) + 97323.8\,(SFCMAX) + 25083.6\,(CS) + 27.4\,(RPMMAX)$$

TERMS:

AF	= Maximum Rated Air Flow/Sea Level Static
CS	= Compressor Stages, Number of, in an engine
RPMMAX	= Revolutions per Minute (maximum)
SFCMAX	= Specific Fuel Consumption (maximum)
TIT	= Turbine Inlet Temperature/SLS

Table 4

Models 3, 4, & 6 (18:56)

Model Number	Cost Equation
3	Cost = -70075.5 + 828.0 (DMATRL) - 20.5 (THRCR) +33652.9 (CS) - 14.1 (THRMAX)
4	Cost = 840698.8 + 394.5 (CMATRL) - 937.0 (AF) -102112.0 (TWR) - 75.0 (DMATRL)
6	ln (cost) = -.6682 + 2.28528 ln (MF) - .44925 ln (DMATRL) -1.91158 ln (TWR) - 2.44975 ln (PR)

TERMS:

AF = Air Flow
CMATRL = "C" Material
DMATRL = "D" Material
MF = Maurer Factor
PR = Pressure Ratio
THRCR = Cruise Thrust
THRMAX = Maximum Thrust
TWR = Thrust to Weight Ratio

incorporates the Maurer Factor CER. The MF, developed by the late Mr. Richard J. Maurer, was a parameter used in the Navy cost estimation models. The basic concept behind the MF method was that the cost of a turbine engine is related to the materials required to build the engine (3:2-5).

In the mid 1960s the Navy began extensive research into the "why and how" of engine costs. As higher technology engines became a reality, the Navy realized that its costing methods were not adequate. After surveying existing costing methodologies and CERs, the Navy decided that the engine parameters used in its cost estimation models were not valid. Instead, the Navy developed the basic rationale that the cost of an engine, in great part if not entirely, is governed by the type of material as well as the weight of the raw material employed in the manufacture of an engine (3:2-5).

> This rationale assumes that most of the physical and thermodynamic technology areas associated with engine-compressor stage loading, maximum turbine temperatures, specific weights, etc.--are closely interrelated with the metallurgical technologies. This assumption is probably more true of the aircraft industry than any other aerospace industry because of the severe stress and temperature environment experienced by a jet engine [3:2-5].

As a result of this concept of the relationship of materials to cost, the Navy began initial efforts in defining a material parameter to describe engine costs. Mr. Richard Maurer did extensive work in classifying all the materials used in a jet engine into seven material categories, and

developed a weighting factor for each category (Table 5). In developing the weighting factor for the different metals, Maurer considered both the cost of materials and machining costs, including labor and production costs (3:2-5).

Table 5

Material Classification and Weighting Factors (18:99)

Material Classification	Percentage of Nickel + Cobalt	Weighting Factor
Conventional	0 - 24	1.00
A	25 - 44	6.65
Titanium (T)	-	10.50
B	45 - 59	13.95
C	60 - 69	24.00
D	70	29.75
E	>70	40.00

In order to use the MF in engine cost estimation, the gross weight of all the materials required to build an engine must be known. The MF is determined by the summation of the raw materials weight times their relative weighting factor. The MF equation is

$$MF = \sum_{i=1}^{n} w_i f_i$$

where w_i is the gross weight before machining of the i^{th} part and f_i is the corresponding weighting factor (3:2-9).

Next, linear regression is used to develop a cost estimating relationship in which the MF is the independent variable, and production cost is the dependent variable (Figure 2) (3:2-8 to 2-12).

A variation of the original MF technique is the estimated MF. Engine performance parameters, such as weight and turbine inlet temperature are used in a parametric equation to determine an estimated MF. The estimated MF is then used in the same manner as the actual MF to determine engine production costs (3:2-14).

The Navy's work with the MF has enticed other organizations to study the MF. Detroit Diesel Allison (DDA) has conducted extensive research concerning the MF approach. DDA's work with the MF resulted in some minor changes in the weighting factors for the materials. Also, DDA felt that since the MF is based on the total weight of raw materials in an engine, some factor was required to indicate the degree of efficiency of material utilization. They introduced also a "K factor" which included a measure of plant efficiency, effect on manufacturing cost due to production rate, and effect of total production quantity on cost (23:10-4 to 10-11). DDA believes that the main advantage of the MF method is that it is a simplified cost estimation method that yields useable results.

There are other cost estimation methods, such as the accounting-engineering method mentioned earlier, which yield

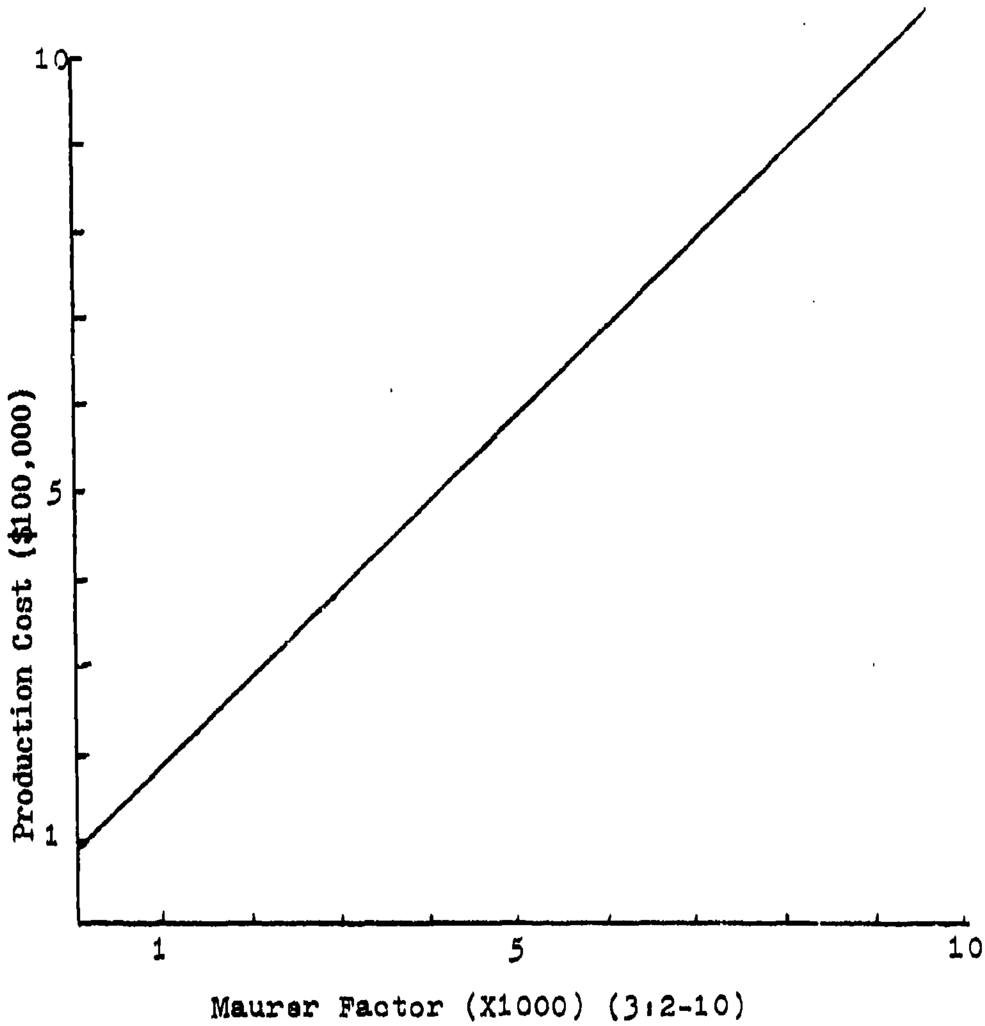


Figure 2

Calculated MF

better results but also require many more man-hours and much more detailed information about the engine. Ordinarily this information would not be available in the early stage of engine development (23:10-18).

The Learning Curve

Another aspect that should be taken into account in cost estimation models is the learning curve. The basic theory is that when a new task is undertaken by an individual or group, continuous repetition of that task will tend to improve efficiency (4:3). The learning process prevails in many industries; its existence has been verified by empirical data and controlled tests. A Rand report stated that

> . . . the basis of learning-curve theory is that each time the total quantity of items produced doubles, the cost per item is reduced to a constant percentage of its previous cost [2:93].

For example, in a manufacturing process possessing an 80% learning curve, the cost of producing the 2nd unit would be 80% of the cost of producing the 1st unit, and the cost of producing the 32nd unit would be 80% of the cost of producing the 16th unit (17). The learning curve seems to fit most appropriately in situations where there is: (1) a high proportion of manual labor, (2) uninterrupted production, (3) production of complex items, (4) no major technological changes, (5) continuous pressure to improve, or (6) no external rate changes (16). Although there are

many factors contributing to the learning curve theory, the most commonly mentioned are:

1. Job familiarization by workmen.

2. General improvement in plant coordination and organization.

3. Development of more efficient operations.

4. Substitution of casts or forged components for machined components.

5. Improvements in overall management (2:94).

Rand also believed that a learning curve exists for unit materials cost. Workmen learn to work more efficiently with the raw materials, and management learns to order materials in shapes and sizes which are more appropriate for the job, thereby reducing the waste involved in fabrication. The result is a reduction in overall material cost as the learning process continues (2:95-96).

Since the MF is based on the relationship of materials to production cost, this research effort will investigate the application of the learning curve to the MF. (See Appendix B for explanation of the learning curve.)

Objectives

The objective of this research study was to determine if the Maurer Factor cost estimation method could be used by the Propulsion Branch of the Air Force Aero Propulsion Laboratory. The study will include an examination of the procedures required to use the MF cost estimation method.

The accuracy of the results obtained from the MF technique and the amount of time and effort required to use the technique will determine the value of the technique to the Propulsion Branch.

The research effort will also investigate the possible application of the learning curve theory to turbine engine cost.

Research Questions

1. What steps are necessary to develop and use the Maurer Factor cost estimation model?

2. What results can be achieved concerning turbine engine cost estimation in the early development stage by using the Maurer Factor cost estimation model?

3. Is the learning curve applicable in turbine engine cost estimation?

4. How can the learning curve be incorporated with the Maurer Factor technique?

Research Hypothesis

A model based on engine performance parameters can be developed which will estimate the Maurer Factor.

Summary

Increasing costs in aircraft weapons systems have been evidenced by the acquisition managers. In an attempt to use limited funds more efficiently, cost analysts require cost estimation techniques which will accurately predict

future costs. The Propulsion Branch analysts are familiar with four estimation techniques--(1) the Rand model, (2) the Grumman model, (3) the Mullineaux and Yanke model, and (4) the Maurer Factor model. However, they have specifically requested the study of the MF for use in their work with turbine engines. The MF is a statistical and not an industrial-engineering approach of achieving a cost estimate. This research will analyze the MF's usefulness in predicting turbine engine production costs in the early development stage.

Chapter 3

RESEARCH METHODOLOGY

Overview

The research methodology was designed to determine the estimated cost of turbine engines using the Maurer Factor (MF) technique. Additionally, a model was developed which will estimate the MF. In this model, estimated Maurer Factor (EMF) was the dependent variable and engine performance parameters and engine categories were the independent variables.

Variables of Interest

The variables of interest included turbine engine materials, engine performance parameters, and engine classification based on afterburner versus non-afterburner. The materials variable represented the summation of all materials in a turbine engine. RPM, turbine inlet temperature, and thrust were the performance parameters used in developing the EMF model (Table 6).

Justification of Variable Selection

As discussed earlier, several studies indicated that engine materials were an important cost-driving factor

Table 6

List of Independent Variables

X_1 = Dry Weight (WGT)	X_{10} = Cruise Thrust
X_2 = Engine Length (L)	X_{11} = RPM, Maximum
X_3 = Engine Diameter (D)	X_{12} = RPM, Cruise
X_4 = Number of Compressor Stages	X_{13} = Specific Fuel Consumption, Maximum
X_5 = Number of Turbine Stages	X_{14} = Specific Fuel Consumption, Cruise
X_6 = Turbine Inlet Temperature (TIT)	X_{15} = Afterburner (AB)
X_7 = Air Flow (AF)	X_{16} = Overall Press Ratio (PRESS)
X_8 = Thrust to Weight Ratio (T/W)	X_{17} = Model Qualification Test Based on Grumman Base Year of 1900 (MQTYR)
X_9 = Maximum Thrust	X_{18} = Sea Level Limiting Mach Number

(3; 15; 18; 23). For this study the MF was used as the material factor in the cost estimation model.

The variables listed in Table 6 were used to develop the EMF model. These variables were determined through discussion with the Propulsion Branch cost analysts and through information gained from research studies conducted by the Navy and the Rand Corporation (8; 17; 20; 27). Several combinations of these independent variables were used in developing the model.

Selection of Independent Variables

Three basic requirements were considered in selecting variables for the cost estimation model.

1. The variable (MF) had to exhibit a logical relationship as a cost-driving factor (29:374-376).

2. The variables in the EMF model had to show a logical relationship to MF.

3. The model is proposed for use by the Propulsion Branch; therefore, independent variables were selected which could be supported by data available to the cost analyst in the early development stage of an engine.

Method of Data Collection

Two methods were used to obtain data. First, the data base created by Captains Mullineaux and Yanke was used. The data base contains engine performance parameters for 93

turbine engines. However, the gross weight of individual components in some of the engines was not available; therefore, these engines could not be used for MF calculations.

Another major source of data was the USAF Propulsion Characteristics Summary (Airbreathing). This document is commonly referred to as the Gray Book. Data in the Gray Book concerning engine production lots and engine prices were used for investigating learning curve characteristics in turbine engine production. Also, the data collection plan included the use of the Navy's equivalent to the Gray Book.

The DD Form 346, Abbreviated Summary Bill of Materials, was another data source. The 346 gives a breakdown of an engine by components and lists the gross weight of these components, before machining, along with the type of material of each component. The 346 is supplied to the Air Force by the contractor, and the data contained in it are vital to performing MF computations. An example of the data found on the DD Form 346 is shown in Table 7.

The final source of data was material type and gross weight of engine components as supplied by engine manufacturers. A complete set of this type of data was obtained from the manufacturer of one of the validation engines (Appendix C).

Table 7

Sample Information from DD Form 346

Name of Material	Specification (AMS)	Gross Wt. (lbs)	Material Classification
4640-Alloy Steel	3004	12	Conv
Incoloy T-SST	5531	7	B
L605-SST	5530	58	B
.	.	.	.
.	.	.	.
.	.	.	.
Rene 41-SST	4900	1	T

Before the data obtained from the DD Form 346 and from individual contractors could be used for MF computations, the different materials for all of the engine components were classified and assigned to one of the seven categories shown in Table 5. The classification involved several steps.

First, the different alloys were assigned an Aerospace Material Specification (AMS) number (13:1-31). Each AMS number was assigned to one of the seven MF categories shown in Table 5. The AMS conversion tables used by Capts Mullineaux and Yanke were used to categorize the AMS numbers by MF category (18:101-103). An example of this table is shown in Table 8. A complete explanation of the materials classification process is in Appendix C.

Population and Sample Description

The population consisted of all turbine engines which have been used in United States military aircraft and advanced engines currently under development for possible use in future weapon systems.

The research conducted for the literature review indicated that data pertinent to the calculation of the MF may be difficult to obtain. Therefore, a sample of opportunity was used in our data collection effort.

Table 8

Aerospace Materials Specification (AMS) Conversion Table

AMS	Classification
3004-4893	Conv
4900-4966	T
5342-5344	A
.	.
.	.
.	.
.	.
5530-5532	B

Model Justification

The objectives of the study included an investigation of the MF process and the development of an estimated MF model. The MF cost estimation concept was chosen because:

1. A model is needed which is not complicated and obtains reasonable results. Engineers and cost analysts working in the turbine engine field consider an estimate within 25 percent of the actual cost to be reasonable (17).

2. Engine cost appears to be highly related to materials; therefore, the model should be sensitive to materials (3:2-5).

3. The higher the engineering technology in an engine the higher the cost; therefore, the model must be sensitive to technology changes (13:81-82). Technology is compensated for in the MF model through the weighting factors assigned to the seven MF materials classifications (3:2-5).

The development of the EMF model was studied because the material data required to compute the actual MF may not be readily available to cost analysts in the Propulsion Branch. Since the literature review indicated that the use of a material factor in the turbine engine cost estimation model is appropriate, a relationship between engine parameters and MF was used to develop the EMF model. The Navy's successful use of the MF technique verifies the importance of the material factor in estimating engine cost (7).

Model Development

One part of this research effort was directed toward developing a model that could be used to estimate the MF. The EMF can then be used in the MF cost estimation models developed by the Navy. To develop the EMF model, it was necessary to establish and verify appropriate relationships between engine parameters and MF.

After the appropriate variables were identified, such as the relationship of engine air flow and MF; engine thrust and MF; and turbine inlet temperature and MF, some meaningful way had to be used to combine these variables into a useable model. Regression analysis was used to analyze and combine the variables into a model which resulted in an EMF model.

Regression Analysis

Multiple regression was used to develop the EMF model. Multiple regression is an extension of the simple linear regression technique discussed in Chapter 2. However, in multiple regression a number of independent variables may be used. The advantage of this method is that the effects of several independent variables on the dependent variable may be determined. Also as independent variables are added to the model, the amount of unexplained variation in the model is reduced (29:359-362).

The independent variables were the engine performance parameters as listed in Table 6. The dependent variable was

MF. An explanation of the multiple regression technique used to develop the EMF model is given in Appendix D.

Validation Process

The Maurer Factor technique. Before EMF model validation could be accomplished, the cost estimating relationship of calculated MF to cost had to be validated. The calculated MF for five engines was used in three MF models developed by the Navy. Hereafter, these engines will be referred to as validation engines 1, 6, 7, 8, and 9. Engine 1 is an advanced technology engine, and engines 6, 7, 8, and 9 are turbojet engines currently in use. The estimated costs of the validation engines were compared to their actual costs. Engines 1, 6, 7, 8, and 9 were selected as the validation engines because the data required to compute the MF for these engines were available, and their actual costs could be determined. Therefore, a meaningful comparison between actual engine cost and the estimated cost could be made. After the Navy MF models had been validated, the EMF model validation could be accomplished.

Estimated Maurer Factor model validation. The EMF models were developed using data from the Mullineaux and Yanke data base. Five advanced technology engines were used to validate the EMF models; hereafter referred to as engines 1, 2, 3, 4, and 5.

Certain performance parameters for engines 1, 2, 3, 4, and 5 were used in the EMF models to arrive at an EMF. The computed EMF was then used in the three Navy MF models. The resultant estimated costs were compared to the actual cost of engines 1, 2, 3, 4, and 5.

In order to obtain a realistic validation of the EMF models, engines 1, 2, 3, 4, and 5 were not used as data points in developing the EMF models.

Selected test criterion. The statistical significance of the model was determined using F-test and t-tests with the level of significance set at $\alpha = .05$. (See Appendix D for further explanation of these tests.)

Summary List of Limitations

1. The gross weights of some of the engine components used in calculating the Maurer Factor were estimates. The estimates were made by the engine manufacturers and were assumed to be accurate (17).

2. The independent variable list identified may not be all-inclusive (17).

Summary List of Assumptions

1. Concerning the independent variables:

a. The regression models developed by the Navy were assumed to represent an accurate regression of turbine engine cost on Maurer Factor (3:2-13),

b. The engine performance parameters used in developing the EMF regression models were assumed to be the most representative of the entire set of possible performance parameters, and

c. The independent variables met the necessary criteria for regression analysis. A list of these criteria can be found in Appendix D.

2. Historical data of past jet engines could be used to predict the costs of future jet engines.

Chapter 4

DATA ANALYSIS AND FINDINGS

Introduction

In this chapter a detailed analysis of the Maurer Factor (MF) technique and the estimated Maurer Factor (EMF) models are presented. The results of the estimated costs of the validation engines obtained using the MF technique are discussed in an attempt to determine its validity. Also, a statistical analysis of the EMF models is presented. The EMF models are discussed in terms of the statistical findings for each model and the results of the validation process using the validation engines. The chapter is summarized by addressing the research questions and the research hypothesis.

Maurer Factor Cost Estimating Technique

Learning curve cost adjustment. The learning curve theory was used to adjust the cost of the validation engines to the cumulative average cost of 1500 engines. The adjustment was required because the Navy MF cost estimation models were based on the cumulative average manufacturing cost of 1500 engines, and the costs of the validation engines were all based on costs other than the cumulative

average cost of 1500 engines. To make a valid comparison of the actual cost to the estimated cost, the actual cost and the estimated cost had to have the same cumulative average cost basis.

Since validation engines 6, 7, 8, and 9 were engines in the inventory, historical cost data for these engines were available. The percent of learning for these engines was calculated using the computations shown in Appendix B. After the percent of learning was computed, the cumulative average cost of engines 6, 7, 8, and 9 was calculated. A summary of the calculations is presented in Table 9.

Because validation engines 1, 2, 3, 4, and 5 were proposed advanced technology engines, no historical data were available to calculate the percent of learning. The learning figures supplied by the manufacturers were used to adjust the costs of validation engines 1, 2, 3, 4, and 5 to cumulative average costs (Appendix B). A summary of these computations is shown in Table 9.

<u>Profit and General and Administrative cost adjustments</u>. In addition to the learning curve cost adjustment to the validation engines, the engine costs were adjusted for profit and general and administrative (G&A) costs. This adjustment was necessary because the Navy cost models gave an estimated cumulative average manufacturing cost, but the dollar amounts of the validation engines were total selling price to DOD. The manufacturing

Table 9

Percent Learning for Validation Engines

Validation Engine Number	Calculated Percent of Learning	Manufacturer Supplied Percent of Learning	Cumulative Average Mfg Cost[a] of 1500 Engines
1	--	90%	266,658[b]
2	--	87%	1,100,012[b]
3	--	89%	328,069[b]
4	--	89%	259,410[b]
5	--	90/85%	148,483[b]
6	93%	--	277,535[c]
7	99%	--	288,006[c]
8	100%	--	240,009[c]
9	91%	--	328,919[c]

[a]All cost figures in FY78 dollars.

[b]Manufacturing cost of basic engine less controls and accessories.

[c]Manufacturing cost of basic engine, controls, and accessories.

costs of the validation engines were computed by removing profit and G&A costs from the selling price. The profit and G&A rates were provided by the Propulsion Branch (Appendix E) (17).

Results of Maurer Factor validation. The adjusted costs of validation engines 1, 6, 7, 8, and 9 shown in Table 9 were used as part of the analysis of the MF cost estimation technique. Engines 1, 6, 7, 8, and 9 were used because the data required to compute the MF were available for these engines. Appendix C is a step-by-step description of the MF calculations for validation engine 1. The same procedure was used for engines 6, 7, 8, and 9.

As explained in Chapter 2, the calculated MF is the independent variable in a simple regression equation of cost on MF. The Navy has developed three MF cost models. (See Table 10 for Navy models.) In an attempt to verify the validity of the MF technique, the calculated MFs for validation engines 1, 6, 7, 8, and 9 were used in the three Navy models. The results of the computations are shown in Table 11 and Figures 3, 4, and 5.

Analysis of validation results. In the case of turbine engines, a cost estimation model is considered to be a useable model when it predicts cost within 25 percent of the actual cost (17). Validation engines 1, 6, and 9 met the 25 percent criterion.

Table 10

Navy Maurer Factor Cost Models

Model 1	$CAMC^a = 4.453\ (MF) + 3582$
Model 2	$CAMC^a = 1.875\ (MF) + 48296$
Model 3	$CAMC^a = 1.669\ (MF) + 73889$

[a] CAMC = Cumulative average manufacturing cost (FY65 dollars) per engine based on 1500 engines.

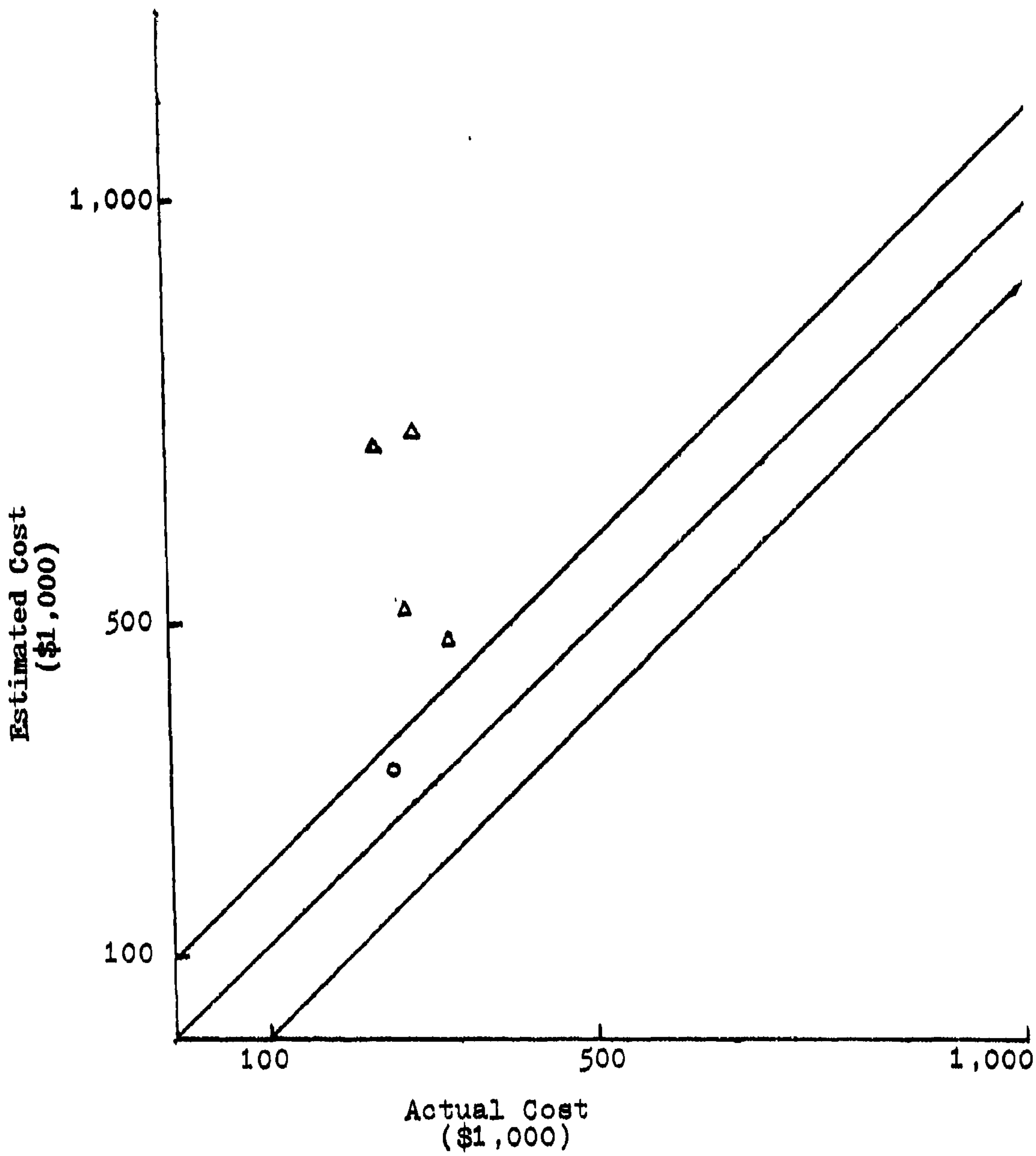
Table 11

Summary of MF Estimated Cost vs Actual Cost

Engine Number	MF	Mfg Cost	Est Cost Navy Mod 1	% Error Navy Mod 1	Est Cost Navy Mod 2	% Error Navy Mod 2	Est Cost Navy Mod 3	% Error Navy Mod 3
1	35,247	266,658	320,429	20	228,310	-14	264,902	-.6
6	57,207	277,535	514,018	85	307,774	11	338,058	22
7	81,653	288,006	732,900	154	399,054	39	419,497	46
8	80,880	240,009	726,030	203	396,188	65	416,922	73
9	54,057	328,919	487,620	48	296,766	-10	327,565	-.4

Cumulative Average Manufacturing Cost of 1500 engines in FY78 dollars

$$\% \text{ Error} = \frac{\text{estimated cost} - \text{actual cost}}{\text{actual cost}} \times 100$$

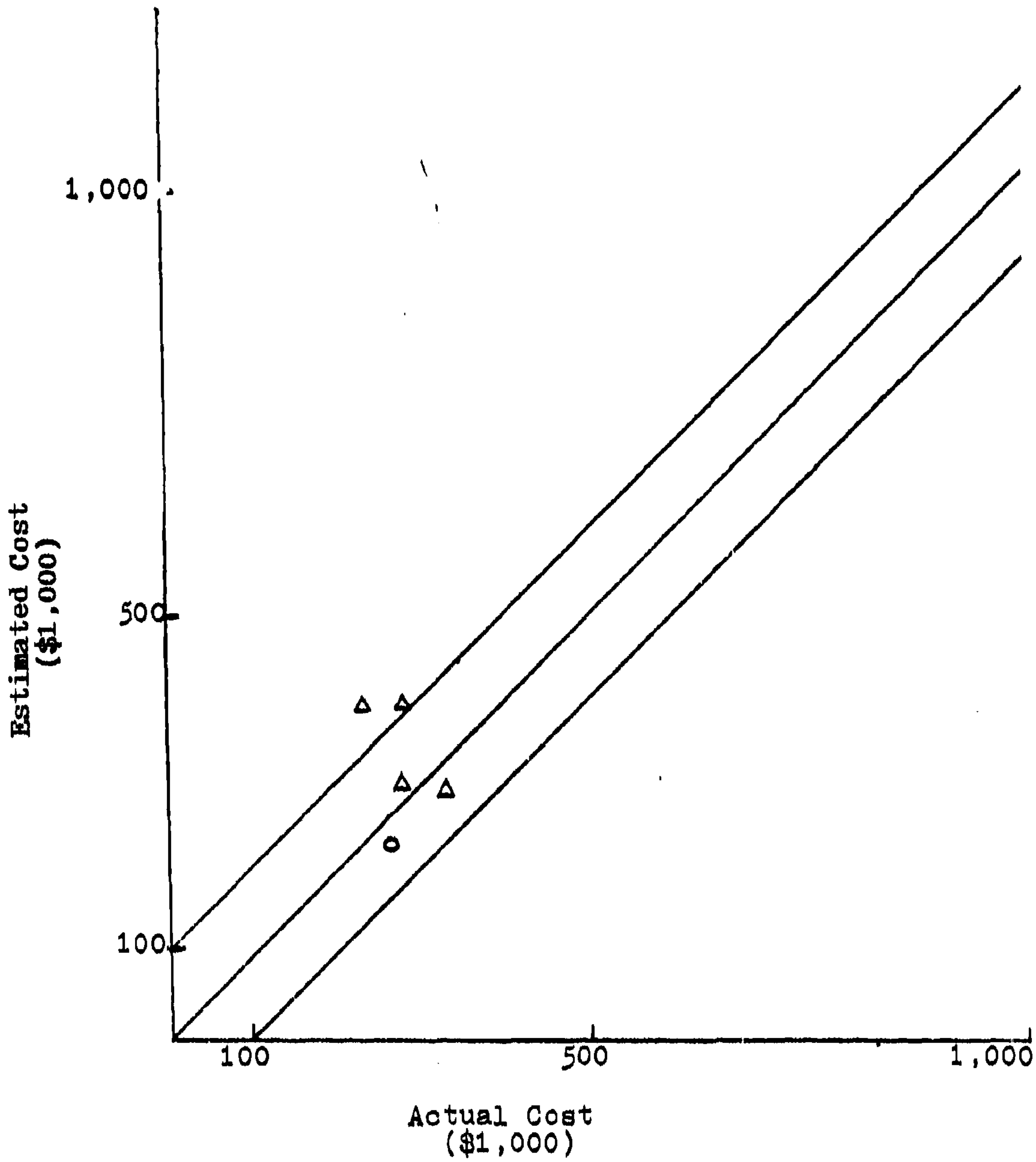


o - engines with thrust ≤ 10,000

Δ - engines with thrust > 10,000

Figure 3

Navy Model 1

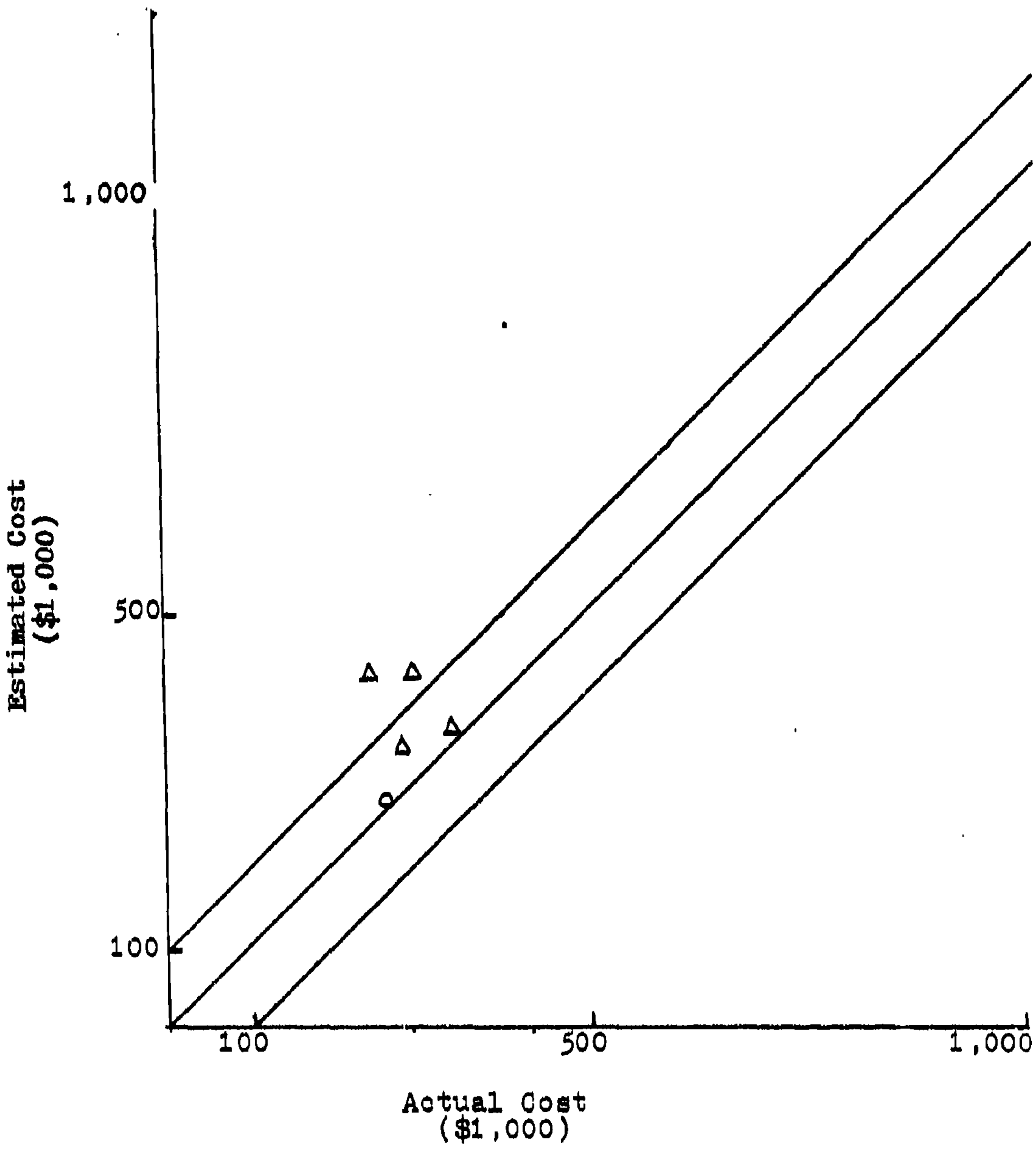


O - engine with thrust ≤ 10,000

Δ - engine with thrust > 10,000

Figure 4

Navy Model 2



o - engines with thrust ≤ 10,000 lbs

Δ - engines with thrust > 10,000 lbs

Figure 5

Navy Model 3

In an attempt to determine which of the three Navy MF models was the best, it was noted that the engine thrust or possibly the size of the MF may determine which model gives the best results. It appeared that engines with a maximum thrust of 10,000 pounds or less obtained the best results using Model 3, but that those with thrust greater than 10,000 pounds obtained the best results using Model 2. The MF size may also be a driving factor. In this case Navy Model 3 performed best when the MF was less than 55,000, and Model 2 seemed to achieve better results with a MF above 55,000. The MF size corresponded to the amount of thrust. Engines with a MF of less than 55,000 also had less than 10,000 pounds of thrust. Those with a MF greater than 55,000 had more than 10,000 pounds of thrust.

Estimated Maurer Factor Models

Overview. The objective was to develop an estimated Maurer Factor (EMF) model which could be used in the early development stage of a turbine engine. This section describes the EMF models that were developed. The discussion includes a description of the data bases, a statistical analysis of selected models, and the results of the validation of the models.

Model development. The EMF models were developed using the multiple regression technique (Appendix D). The

regression was performed using four data bases hereafter referred to as the Basic Data Base, the Grumman Parameters Data Base, the Turbofan Data Base, and the Turbojet Data Base. The following is a description of the contents of each data base.

Basic Data Base. The Basic Data Base consisted of the calculated MF and engine parameters for 35 turbine engines. The data for these engines were obtained from research conducted by Mullineaux and Yanke, from analysts at the Naval Air Development Center, from the Air Force Gray Book, and from the Navy version of the Air Force Gray Book. Table 12 is a summary of the variables in the Basic Data Base.

Grumman Parameters Data Base. The Grumman Parameters Data Base contained the calculated MF and some of the engine parameters used in the Grumman cost model discussed in Chapter 2. The Grumman Parameters were selected because of research conducted in which it was determined that the Grumman model yielded the best cost estimation results as compared to the Rand and Mullineaux and Yanke models (17). Fifteen engines were used in this data base. Table 13 is a summary of the variables in the Grumman Parameters Data Base.

Turbofan and Turbojet Data Base. The Turbofan and Turbojet Data Bases were developed by separating the engines

Table 12

Basic Data Base Variables

Variable Name	Variable Abbreviation
Calculated Maurer Factor	MF
Engine Dry Weight (pounds)	WT
Air Flow	AF
Turbine Inlet Temperature (Degrees F)	TIT
Engine Diameter (inches)	DIA
Thrust to Weight Ratio	TW
Afterburner	AB
Maximum Specific Fuel Consumption	MSFC
Maximum Thrust	MTRST

Table 13

Grumman Parameters Data Base Variables

Variable Name	Variable Abbreviation
Maurer Factor	MF
Model Qualification Test Based on Grumman Base Year 1900	MQTYR
Overall Pressure Ratio	PRESS
Sea Level Limiting Mach	MACH
Afterburner	AB

in the Basic Data Base into two categories--turbofan and turbojet. The parameters in the Basic Data Base were also used in the Turbofan and Turbojet Data Bases. The Turbofan Data Base contained 11 engines and the Turbojet Data Base contained 24 engines.

Statistical Analysis

Overview. A statistical analysis of the EMF models was conducted to determine which models were statistically significant. The statistical significance of a model is determined by measuring the dependence of a variable on a set of independent variables. A subjective determination of the level of significance for each EMF model and its independent variables was set at the $\alpha = .05$ level (29:243-245).

As presented in Chapter 3, the technique of multiple regression was used to develop the EMF models. With the aid of a computer subprogram, REGRESSION, 13 initial models were developed. The subprogram produced a printout with the information required to analyze each model and its independent variables. With this printout, it was then determined that all models except Model 11 were statistically significant at the $\alpha = .05$ level. Once each of the 13 models was tested for significance, the independent variables were analyzed as to their significance in their particular model. (See Appendix D for further details.) After the analysis of

the overall models and the individual variables was completed, the next step of the analysis was performed.

Each of the independent variables was analyzed for significance in its EMF model. The 13 EMF models were then run through the multiple regression subprogram, but with this run only the previously determined significant variables were included. Table 14 is a summary of the results of the two-step statistical analysis. The table includes the R^2 value and the F value for the overall models with all independent variables included. The table also shows the R^2 and the F value for the same models with the statistically insignificant independent variables excluded.

The EMF models were grouped according to the data base used to develop the model. The following is a discussion of the results of the statistical tests performed on the final EMF models--that is the models with only the significant variables included. Of particular interest was the R^2 value for the overall model, the F value for the overall model, and the t statistic for the individual variable coefficients.

<u>Basic Models</u>. The Basic EMF models (Models 1, 2, 3, 4, 5, and 9) which were developed using the Basic Data Base are summarized in Table 15. The models and the independent variables were tested for statistical significance at the $\alpha = .05$ level. All of the final EMF models shown in Table 15 were significant as were the independent variables.

Table 14

Model Summary

Model Number	Independent Variables[a]	R^2	Model F Value	Statistically Significant Variables[b]	R^2	Model F Value
1	TIT, AF, MTRST, AB	.77	25.53	TIT	.61	7.22[c]
2	TIT, AB, MSFC	.63	17.47	TIT	.61	7.22[c]
3	TIT, AF, AB, MSFC	.81	31.82	TIT, AF, AB, MSFC	.81	31.82
4	AF, MSFC, AB	.63	17.98	AF, MSFC	.61	51.31
5	TIT, MSFC, AB	.46	8.81	TIT	.44	5.10[c]
6	PRESS, MQTYR, AB, MACH	.92	30.50	PRESS	.88	9.58[c]
7	PRESS, MQTYR	.92	44.26	PRESS	.88	9.58[c]
8	PRESS, AB	.89	50.67	PRESS	.88	9.58[c]
9	AF, MSFC, TW	.67	20.95	AF, MSFC	.61	51.31
10	MTRST, MSFC, AF, AB	.61	7.47	MTRST	.39	3.77[c]
11	AF, AB, MSFC, TIT	.32	2.21	AF	.25	2.68[c]

Table 14 (continued)

Model Number	Independent Variables[a]	R^2	Model	Statistically Significant Variables[b]	R^2	Model F Value
12	TIT, AF, MSFC, AB	.95	26.79	TIT, AF	.77	13.18
13	MTRST, AB, AF, TIT	.50	6.67	MTRST, AB	.49	10.10

[a]These were all independent variables used in the regression model

[b]Variables were tested for statistical significance at $\alpha = .05$ level. Regression with only statistically significant variables in the model.

[c]For simple linear regression models, this is the t statistic which is the square root of the F value for the overall multiple regression model.

Table 15

Summary of Basic EMF Models

Model Number	EMF Equation
1, 2	EMF = -422656.90933 + 297.84749 (TIT)
3	EMF = -348352.779 + 194.695 (TIT) + 200.864 (AF) + 57779.67 (MSFC) -68144.103 (AB)
4, 9	EMF = -35835.54 + 302.199 (AF) + 34980.385 (MSFC)
5	ln EMF = -19.2574 + 4.0784 ln (TIT)

The R^2 value in a multiple regression model is used as an indicator of the strength of the model. It was believed that the EMF models should have an R^2 of at least .80. Of the Basic EMF models, only Model 3 met the .80 criterion. Because of the low R^2 of Models 1, 2, 4, and 5, their use as an estimator of turbine engine costs was questionable.

Grumman Models. The Grumman EMF models (Models 6, 7, and 8) which were developed using the Grumman Parameters Data Base are summarized in Table 16. All of the Grumman EMF models shown in Table 16 were statistically significant at the $\alpha = .05$ level as were the independent variables. The final version of EMF Models 6, 7, and 8 were the same because when the insignificant variables were eliminated, PRESS was the only remaining significant variable.

Table 16

Summary of Grumman EMF Models

Model Number	EMF Equation
6, 7, 8	$\ln EMF = 3.18165 + 3.10309 \ln (PRESS)$

The R^2 values for the Grumman EMF models were above the desired level of .80. Therefore, the possibility existed that these models could be used as predictors of turbine engine costs.

Turbojet Models. The Turbojet EMF models (Models 10, 11, and 13) which were developed using the Turbojet Data Base are shown in Table 17. All of the models shown in Table 17 were significant at the $\alpha = .05$ level as were the independent variables.

Table 17

Summary of Turbojet EMF Models

Model Number	EMF Equation
10	EMF = 11777.726 + 2.968 (MTRST)
11	EMF = 6015.97761 + 276.16571 (AF)
13	EMF = 3998.4245 + 4.318 (MTRST) -20990.7223 (AB)

The R^2 value for the Turbojet EMF models did not meet the .80 criterion. Therefore, the use of these models as predictors of turbine engine costs was questionable.

Turbofan Models. The Turbofan EMF model (Model 12) which was developed using the Turbofan Data Base is shown in Table 18. The overall model as well as the independent variables was statistically significant at the $\alpha = .05$ level.

The R^2 value for this model fell slightly short of meeting the .80 criterion.

Summary. The statistical ana ysis of the EMF models developed using multiple and simple linear regression was

Table 18

Summary of Turbofan EMF Model

Model Number	EMF Equation
12	$EMF = -497452.045 + 317.7099\ (TIT) + 120.38657\ (AF)$

performed to determine which of the models were statistically significant. The desired R^2 level and the α level were subjectively selected by the researchers so that the relative statistical strength of the different EMF models could be determined.

EMF Model Validation

After the statistical analysis was performed, the EMF models were validated using validation engines 1, 2, 3, 4, and 5. The purpose of the validation was to determine which EMF models could be used with the Navy MF models to produce useable cost estimates. A useable cost estimate was considered to be an estimate within 25 percent of actual cost (17). The percent was calculated using the following:

$$\text{Percent of error} = \frac{\text{Estimated Mfg cost-Actual Cost}}{\text{Actual Mfg Cost}} \times 100$$

To determine the estimated costs of a validation engine, two steps were necessary. First, engine parameters were used to calculate an EMF. Next, the resultant EMF was used in the three Navy models to compute the estimated cumulative average manufacturing cost. This estimated cost was then compared to the actual engine cost using the percent of error formula shown above.

Since the dollar amounts for engines 1, 2, 3, 4, and 5 were proposed selling prices, the amounts had to be converted to manufacturing costs. The cost conversion, showing the removal of profit and G&A costs, is given in

Appendix E. Also the costs for the engine controls and accessories were removed from the total engine cost. Therefore, all costs in the next section are the cumulative average manufacturing costs of engines without controls and accessories in FY78 dollars.

Analysis of Validation Results

In analyzing the results of the validation process, of primary importance was the cost figure obtained using the overall MF process, that is, using the parameters for a particular engine in one of the EMF models and then using the resultant EMF in the Navy MF models to arrive at a final cost estimate. Validation engines 1, 2, 3, 4, and 5 were used with 9 of the EMF models previously discussed. Models 2, 7, 8, and 9 were not used because they were duplications of other models. The resulting EMFs were used in the three Navy MF models, and the estimated costs were compared to actual validation engine costs. A summary of these results is shown in Tables 19 through 27.

Based on the results shown in these tables, EMF Models 1, 3, 6, and 12 could be eliminated without any further analysis because their percent of error exceeded 25 percent of the actual cost. The models that were somewhat close to meeting the 25 percent estimating criterion were EMF Models 4, 10, 11, and 13. Analyzing the results given in Tables 21, 24, 25, and 27, it was noted that there was a

Table 19

Cost Comparison of EMF Model 1

Engine Number	Actual Cost	Predicted Cost Navy Mod 1	% Error Navy Mod 1	Predicted Cost Navy Mod 2	% Error Navy Mod 2	Predicted Cost Navy Mod 3	% Error Navy Mod 3
1	266,658	3,199,737	1,100	1,440,684	440	1,344,076	404
2	1,100,012	4,192,490	281	1,858,697	69	1,716,163	56
3	941,084	4,721,952	402	2,081,635	121	1,914,608	103
4	744,131	4,721,952	535	2,081,635	180	1,914,608	157
5	107,015	2,683,501	2,408	1,223,315	1,043	1,150,589	975

Table 20

Cost Comparison of EMF Model 3

Engine Number	Actual Cost	Predicted Cost Navy Mod 1	% Error Navy Mod 1	Predicted Cost Navy Mod 2	% Error Navy Mod 2	Predicted Cost Navy Mod 3	% Error Navy Mod 3
1	266,658	2,089,709	68	977,080	26	931,407	24
2	1,100,012	3,085,115	18	1,392,421	3	1,301,115	2
3	941,084	3,189,152	239	1,436,227	53	1,340,109	42
4	744,131	3,403,473	357	1,526,470	105	1,420,437	91
5	107,015	1,533,489	1,333	739,086	591	719,560	572

Table 21

Cost Comparison of EMF Model 4

Engine Number	Actual Cost	Predicted Cost Navy Mod 1	% Error Navy Mod 1	Predicted Cost Navy Mod 2	% Error Navy Mod 2	Predicted Cost Navy Mod 3	% Error Navy Mod 3
1	266,658	223,596	-16	187,537	-30	228,608	-14
2	1,100,012	1,098,126	-.17%	555,770	-49	556,385	-49
3	941,084	090,607	-3	476,392	-49	485,727	-48
4	744,131	574,761	-23	335,400	-60	360,226	-52
5	107,015	35,370	-67	108,282	1	158,060	48

Table 22

Cost Comparison of EMF Model 5

Engine Number	Actual Cost	Predicted Cost Navy Mod 1	% Error Navy Mod 1	Predicted Cost Navy Mod 2	% Error Navy Mod 2	Predicted Cost Navy Mod 3	% Error Navy Mod 3
1	266,658	394,374	47.90	259,446	-2.70	292,616	9.73
2	1,100,012	449,801	-59.11	282,784	-74.29	313,390	-71.51
3	941,084	479,381	-49.06	295,239	-68.63	324,477	-65.52
4	744,131	479,381	-35.58	295,239	-60.32	324,477	-56.40
5	107,015	365,523	241.56	247,297	131.09	281,802	163.33

Table 23

Cost Comparison of EMF Model 6

Engine Number	Actual Cost	Predicted Cost Navy Mod 1	% Error Navy Mod 1	Predicted Cost Navy Mod 2	% Error Navy Mod 2	Predicted Cost Navy Mod 3	% Error Navy Mod 3
1	266,658	2,339,544	777	1,078,488	304	1,021,673	283
2	1,100,012	5,147,245	368	2,260,711	106	2,074,009	89
3	941,084	2,720,796	189	1,239,019	32	1,164,567	24
4	744,131	322,966	-57	229,378	-69	265,852	-64
5	107,015	2,842,911	2,557	1,290,437	1,106	1,210,336	1,031

Table 24

Cost Comparison of EMF Model 10

Engine Number	Actual Cost	Predicted Cost Navy Mod 1	% Error Navy Mod 1	Predicted Cost Navy Mod 2	% Error Navy Mod 2	Predicted Cost Navy Mod 3	% Error Navy Mod 3
1	266,658	300,292	13	219,831	-18	257,354	-3
2	1,100,012	790,967	-28	426,437	-61	221,071	-80
3	941,084	762,107	-19	414,285	-56	430,444	-54
4	744,131	762,897	3	414,617	-44	430,740	-42
5	107,015	186,754	74	172,024	61	214,799	101

Table 25

Cost Comparison of EMF Model 11

Engine Number	Actual Cost	Predicted Cost Navy Mod 1	% Error Navy Mod 1	Predicted Cost Navy Mod 2	% Error Navy Mod 2	Predicted Cost Navy Mod 3	% Error Navy Mod 3
1	266,658	279,574	5	211,107	-21	249,589	-6
2	1,100,012	743,495	-32	406,448	-63	423,468	-62
3	941,084	679,179	-28	379,367	-60	399,362	-58
4	744,131	529,457	-29	316,324	-57	343,246	-54
5	107,015	202,744	89	178,757	67	220,792	106

Table 26

Cost Comparison of EMF Model 12

Engine Number	Actual Cost	Predicted Cost Navy Mod 1	% Error Navy Mod 1	Predicted Cost Navy Mod 2	% Error Navy Mod 2	Predicted Cost Navy Mod 3	% Error Navy Mod 3
1	266,658	3,093,808	1,060	1,396,081	422	1,304,373	389
2	1,100,012	4,354,993	296	1,927,122	75	1,777,070	62
3	941,084	4,891,735	420	2,153,125	129	1,978,243	110
4	744,131	4,826,460	549	2,125,640	186	1,953,777	163
5	107,015	2,509,656	2,245	1,150,116	975	1,085,431	914

Table 27

Cost Comparison of EMF Model 13

Engine Number	Actual Cost	Predicted Cost Navy Mod 1	% Error Navy Mod 1	Predicted Cost Navy Mod 2	% Error Navy Mod 2	Predicted Cost Navy Mod 3	% Error Navy Mod 3
1	266,658	316,869	19	226,811	-15	263,567	-1
2	1,100,012	844,154	-23	448,832	-59	461,195	-58
3	941,084	802,166	-15	431,152	-54	445,458	-53
4	744,131	989,894	33	510,198	-31	515,819	-31
5	107,015	151,690	42	157,260	47	201,657	88

pattern in the percentage of errors for the different engines using the 3 Navy MF models. As was done previously with the MF validation, a comparison between the percent of error and engine thrust was made in an attempt to explain the pattern that existed.

Engines 2, 3, and 4 had a thrust greater than 25,000 pounds. Engine 1 thrust was less than 10,000 pounds but was very similar to the engines in the data base. Engine 5 thrust was also less than 10,000 pounds but was very much smaller than engines in the data base.

Although engine 5 had a percent of error of 1 using EMF Model 4 and Navy MF Model 2, EMF Model 4 was the only model where engine 5 obtained results that were less than the 25 percent criterion. Since this was the only case where engine 5 came close to the 25 percent criterion, it was decided that the cost of engines of the same type as engine 5 (very small engines with thrust well below 10,000 pounds) could not be determined using the EMF models.

Engine 1, which was considered to be a conventional size engine with less than 25,000 pounds of thrust, met the 25 percent criterion for EMF Models 4, 10, 11, and 13 using all 3 Navy models with one exception--EMF Model 4, Navy Model 2. Therefore, it appeared that EMF Models 4, 10, 11, or 13 could be used with any of the Navy models to estimate the manufacturing cost of a turbine engine with less than 25,000 pounds of thrust. However, the overall best results

were obtained when these EMF models (Models 4, 10, 11, or 13) were used with Navy MF Models 1 or 3.

For engines 2, 3, and 4, which all had thrusts greater than 25,000 pounds, the 25 percent criterion was met in most cases using EMF Models 4, 10, and 13 and Navy MF Model 1. The best overall results for engines 2, 3, and 4 were obtained using EMF Model 4 and Navy MF Model 1.

The analysis of the validation results of the EMF models indicated that some models yielded unuseable cost estimates while other models had results that met the 25 percent estimating criterion. Based on engine thrust, generalizations were made as to what types of engines should be used with the EMF models and the Navy MF models. It was suggested that:

1. The EMF models cannot be used for very small engines (such as engine 5 where the thrust is well below 10,000 pounds).

2. EMF Models 4, 10, 11, or 13 and Navy MF Models 1 or 3 yield results which meet the 25 percent estimating criterion for conventional size engines with less than 25,000 pounds of thrust.

3. EMF Model 4 in conjunction with Navy MF Model 1 yielded the best results for engines with thrust greater than 25,000 pounds.

However, before it could be stated that these EMF models can be used to estimate turbine engine costs, the

results of the statistical tests of these EMF Models had to be considered. Of importance were the statistical significance of the overall model, the statistical significance of the individual regressors, the model R^2 value, and the possibility of autocorrelation in the data. As previously discussed, the final EMF models were shown to be significant as were the individual regressors (Table 14).

Although EMF Models 4, 10, 11, and 13 met the 25 percent estimating criterion, it could not be stated with confidence that these same results would be obtained with other engines because of the low R^2 value of these models. Due to the limited size of the data base, it was believed that a R^2 of at least .80 was required for the EMF models. EMF Models 4, 10, 11, and 13 did not meet the .80 criterion

Another factor that should be considered when dealing with regression models is autocorrelation in the data base. Autocorrelation indicates the presence of a relationship among the residuals; thus, "with positive autocorrelation, the second (or some later) observation tends to resemble, or repeat the first observation, and hence gives little new information [29:626]." The result of autocorrelation is that the estimated regression line is shifted farther from the true regression line. This shift causes the regression constant to be overestimated and the regressor coefficients to be underestimated or vice versa, depending on whether the estimate is above or below the true regression line. The

amount of error is dependent on how much the independent variable of the item being estimated varies from the mean of the independent variable in the data base. The problem with autocorrelation is not that it biases the estimate, since an overestimate is as likely as an underestimate. Rather, the problem is that the estimate may be badly wide of the target (29:627).

Autocorrelation in the data was determined by using the Durbin-Watson statistic. To perform the test, the independent variable of interest was ordered, and then the multiple regression subprogram was used to obtain the Durbin-Watson statistic. This statistic was compared to Durbin-Watson critical values obtained from a Durbin-Watson statistic table (29:720-721). The computer program used to order the data is given in Figure 9 Appendix D. (See Appendix D for detailed explanation of the Durbin-Watson test.)

Using the Durbin-Watson test, it was determined that all EMF models except Model 10 were developed using autocorrelated data.

The existence of autocorrelation was important for two reasons. First, it was stated previously that EMF Models 4, 10, 11, and 13 yielded results which met the 25 percent estimating criterion. However since Models 4, 11, and 13 had autocorrelation, these models should not be used as cost estimators. Because of autocorrelation, the

acceptable results obtained using the validation engines does not guarantee the same results if other engines are used in the models.

The other EMF models (Models 1, 2, 3, 5, 6, 7, 8, 9, and 12) yielded cost estimates that did not meet the 25 percent estimating criterion. It was believed that autocorrelation was the cause of the gross estimates resulting from these models.

Summary. The analysis of the validation results indicated that EMF Models 4, 10, 11, and 13 met the 25 percent estimating criterion. The remaining models did not. However, further statistical analysis of EMF Models 4, 10, 11, and 13 suggested that Models 4, 11, and 13 should not be used as cost estimators because of the presence of autocorrelation. EMF Model 10 met the 25 percent criterion and was not developed from autocorrelated data. However, the R^2 value for Model 10 did not meet the .80 criterion; therefore, Model 10 should not be used as an estimator.

Based on the foregoing analysis, it was concluded that all of the EMF models were unreliable and should not be used to estimate turbine engine costs.

Answers To Research Questions

Research Question 1. What steps are necessary to develop and use the Maurer Factor cost estimation model?

A detailed explanation of the steps involved in the MF technique is given in Appendix C.

<u>Research Question 2</u>. What results can be achieved concerning turbine engine cost estimation in the early development stage by using the Maurer Factor cost estimation model?

The Maurer Factor was computed for validation engines 1, 6, 7, 8, and 9. The computed MF for these engines was then used in the three Navy MF models. According to expert opinion, the results of parametric cost models are considered good if the resultant estimate is within 25 percent of actual cost (17). As shown in Table 11 and Figures 4 and 5, this 25 percent criterion was met by validation engines 1, 6, and 9.

<u>Research Question 3</u>. Is the learning curve applicable in turbine engine cost estimation?

It was believed that the use of learning curve theory is essential in turbine engine cost estimation. The learning curve was used to adjust the actual cost of engines to some basis--that basis being the cumulative average cost per engine based on 1500 engines.

In their thesis, Mullineaux and Yanke have stated that learning curve theory should not be applied to turbine engine production because of the production lot system that is used by engine manufacturers. However, the researchers

and experts in the turbine engine field believe that some learning does take place regardless of what production methods are used (7; 17). The manufacturers of the validation engines used in this thesis all use some form of learning curve (17).

In stating that learning curve theory does apply to turbine engine production, caution must be used when selecting an average percent of learning that can be applied to all engines and all manufacturers. As shown in Appendix B, where the percent of learning for different engines was computed, different engines have different learning curves. Also, as shown in Table 9, different engine manufacturers use different curves.

In summary, the cost analyst using learning curve theory as part of the cost estimation process, must be able to determine which learning curve is appropriate for a particular manufacturer and a particular engine.

Research Question 4. How can the learning curve be incorporated with the Maurer Factor technique?

In this study, learning curve computations were used to adjust all engine costs to the cumulative average cost of 1500 engines. This is the main application of learning curve theory in conjunction with the MF technique (7).

Using the Navy MF models, the estimated cost obtained is the cumulative average cost of an engine based on production of 1500 engines. Using a learning curve, this

cost can be adjusted to the engine cost based on any desired cumulative number of engines. The cost can also be adjusted to the unit cost of an engine based on any n^{th} unit of that engine produced. However, before any of these cost adjustments can be made, the percent of learning for the particular manufacturer must be known (7).

Research Hypothesis

A model based on engine performance parameters can be developed which will estimate the Maurer Factor.

Several EMF models were developed, and all were shown to be statistically significant. Although several of the EMF models met the 25 percent criterion, it was shown that these models should not be used as turbine engine cost estimators because of the low model R^2 and autocorrelation. Therefore with the available data, it was determined that a useable EMF model could not be developed.

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

Overview

As stated in Chapter 1, a cost estimating model is needed which can be used to estimate the cost of a turbine engine early in its development stage. This chapter contains the conclusions related to the analysis of one such technique discussed in previous chapters--the Maurer Factor (MF) cost estimating technique.

One objective of this thesis was to analyze the MF cost estimating technique. The analysis included:

1. A look at what steps were necessary to use the MF cost estimating technique.

2. What results could be obtained using the MF technique.

3. Some of the problems encountered using the MF technique.

The conclusions in this chapter are based on the analysis and on some of the problems encountered in attempting to use the MF technique.

Another area of research was devoted to developing a regression model that could be used to estimate the Maurer Factor. This estimated Maurer Factor (EMF) could be used in conjunction with the Navy MF models to estimate the cost

of a turbine engine. The conclusions for this portion of the research are based on the statistical analysis and the validation results of the EMF models.

Finally, based on the findings concerning the MF technique, some recommendations are presented.

Conclusions

Maurer Factor technique. In analyzing the MF technique, the steps required to use the technique, the results obtained using the technique, and the problems encountered using the technique were considered. The following results were obtained.

To use the MF technique, the MF for a particular engine was calculated. This process included tasks ranging from breaking down an engine into its individual components to determining the gross weight of the individual components. A step-by-step procedure explaining this process is given in Appendix C.

After it was determined that the MF for an engine could be calculated, the cost estimating results using the three Navy MF models (Table 10) were evaluated. The model was considered to be useable if the cost estimate was within 25 percent of the actual engine cost (17). To keep the validation of the MF technique unbiased, validation engines were selected which had not been used in developing the Navy MF cost models. The MF for the validation engines

was calculated and used with the three Navy MF models. The results showed that the 25 percent estimating criterion could be met, depending on which engine was used with a particular Navy model. Based on the validati results (Table 11), it was concluded that the MF technique could be used and would yield cost estimates that met the 25 percent estimating criterion. Also, based on the validation results, it was concluded that engines with a maximum thrust of less than 10,000 pounds obtained the overall best results using Navy MF Model 3 (Table 10). For engines with a thrust value greater than 10,000 pounds, Navy MF Model 2 achieved the best results. Although the estimating criterion was met using the validation engines, it should be noted that the MF validation process was based on a limited number of validation engines.

Several problems were encountered during the validation of the MF cost estimating technique. These problems included a lack of data required to calculate the MF and the questionable currency of the MF weighting factors (Table 5). The following is a discussion of these problems.

A small number of validation engines was used because the data required to compute the MF for an engine was not available. To calculate the MF, the gross weight and type of material of each engine component must be known. The information is contained in the DD Form 346 which should be supplied by the engine manufacturers. However, the form

has not been supplied in most insta es, and as a result, it was impossible to calculate the MF.

Another problem in obtaining the weight information occurred even when the manufacturers did supply the information. Many times manufacturers did not know the actual gross weight of a component before machining. When this occurred, the manufacturers had to estimate the gross weight. For validation engine 1, the manufacturer supplied the data required to calculate the MF, and several of the component weights were estimated.

Another problem was encountered with the MF weighting factors. The weighting factors are used to introduce a difficulty of machinability factor into the MF calculation. The difficulty factor is based on the hardness of different materials. What is not taken into consideration in the weighting factors is the drastic increase in the prices of some materials (7). Although price increases due to inflationary pressures were compensated for by using price index adjustments (Appendix A), the price increase for some materials is much greater than current inflation rates. As a result, the accuracy of the MF technique will probably be affected in the future if some method is not found to compensate for rapidly rising materials prices.

Estimated Maurer Factor models. As discussed throughout this thesis, it was difficult to obtain the data

necessary to calculate the MF. The gross weights of the individual engine components were often not available because the manufacturer had not provided them. Another reason that the data may not be available is because the engine is in a stage of development where specific details about engine components are not known. However, since the MF cost estimating technique did meet the 25 percent estimating criterion as shown in Chapter 4, it was decided to develop a regression model that would estimate the MF. This estimated Maurer Factor (EMF) could then be used with the Navy MF models to estimate the cost of a turbine engine.

The following conclusions were based on the statistical analysis and validation of the EMF models.

1. A high R^2 value does not always indicate the predictive capability of a model. Several of the initially developed EMF models had an R^2 value greater than .90. However, further analysis indicated that many of the independent variables were insignificant. These variables did nothing for the overall model except increase the R^2 value by insignificant amounts. Validation attempts using these initial models resulted in gross estimating errors because of the inclusion of the insignificant variables.

When the insignificant variables in the initial EMF models were removed, the R^2 values dropped. However, model validation showed that several of these final models with low R^2 values in the range of .25 to .65 achieved the

best estimating results. (See Table 14 and Tables 21, 24, 25, and 27.) Therefore, the R^2 value alone should not be used to analyze the predictive capability of a model.

2. The data used to develop a model should be tested for autocorrelation. When several of the EMF models achieved large estimating errors in the validation process, the data was tested for autocorrelation. The test results indicated that autocorrelated data had been used to develop all but one of the EMF models. Therefore, some of the models which achieved acceptable results in the validation process could not be used with any reasonable level of confidence.

3. Of the 13 EMF models developed, Model 10 was the only model that was void of autocorrelation problems and still met the 25 percent estimating criterion. It was concluded that EMF Model 10 should be used in conjunction with Navy MF Models 1 or 3 when estimating the costs of engines with less than 25,000 pounds of thrust. For engines with more than 25,000 pounds of thrust, EMF Model 10 should be used in conjunction with Navy Model 1. For very small engines, the EMF models should not be used.

4. Although EMF Model 10 met the 25 percent estimating criterion, confidence in its predictive capability was limited because of its low R^2 value. If the model had been developed using a larger data base, a low R^2 value would be more acceptable. Also, confidence in EMF Model 10s predictive capability was limited because of the small number of engines used in the validation process.

Recommendations

The recommendations are based on the results of analyzing the validation of the Maurer Factor cost estimating technique. As previously mentioned, one problem encountered in validating the MF technique was lack of data necessary to compute the MF. Therefore, it is recommended that the DD Form 346 be mandatory for engine contracts. This form would enable cost analysts to obtain the gross weights of engine components which are required to compute the MF.

Another problem mentioned was the rapidly increasing prices of raw materials used to build turbine engines. As a possible area for future study, it is recommended that an attempt be made to include a factor in the MF cost estimating process which will compensate for rapidly increasing prices.

Finally, it is recommended that an effort be directed toward increasing the size of the data base used to develop EMF Model 10. The enlargement of the data base should include more modern, advanced technology engines. Copies of the data bases used in this thesis may be obtained from the authors or from Richard McNally, AFAPL/TBP, Wright-Patterson AFB, Ohio.

In conjunction with increasing the data base size, it is recommended that further validation of EMF Model 10 should be accomplished. It is believed that if increased confidence in EMF Model 10 could be developed, the effort

would be beneficial. The research indicated that the Maurer Factor technique is a feasible technique which can meet the 25 percent estimating criterion, but the data required to calculate the MF is not always available. Therefore, a model which could be confidently used to estimate the MF would make the use of the Maurer Factor cost estimating technique more applicable.

In view of increasing defense costs and the decreasing buying power of the defense dollar, effective cost estimating techniques are an important part of defense planning and decision making. It has been the objective of this thesis to contribute in some way to improving cost estimating techniques.

APPENDIX A

INDEX NUMBERS

Index numbers were used in the analysis for the purpose of comparing the proposed cost of an engine with the cost of similar engines procured in past years. Fiscal Year 78 dollars were used in the calculations, therefore all procurement costs were converted from their original FY dollars using a pricing index number (26:13). The number indicates price changes over a period of time and enables the price comparison using a common base, FY78. The following formula was used for the dollar conversion.

$$\frac{\text{Cost (original year)}}{\text{Index}} = \text{FY78 dollars}$$

The index used was taken from AFR 173-10, Vol 1 (C6) attachment 49, 2 May 1977, and follows:

Table 28

Index Numbers

Fiscal Year	Procurement (Index)
1960	.488
61	.489
62	.492
63	.493
64	.495
65	.501
66	.518
67	.536
68	.556
69	.572
70	.594
71	.621
72	.645
73	.672
74	.716
75	.819
76	.880
TQ76	.909
77	.943
78	1.000
79	1.054
80	1.102

APPENDIX B

LEARNING CURVE

As stated in Chapter 2,

> . . . the basis of learning-curve theory is that each time the total quantity of items produced doubles, the cost per item is reduced to a constant percentage of its previous cost [2:93].

Learning curve theory may be expressed mathematically as $Y = AX^B$. The equation, $Y = AX^B$, represents a curve which belongs to the family of curves known as the inverse variation curves (4:11). Inverse variation means that as the independent variable (X) gets larger the dependent variable (Y) gets smaller. Also, Y decreases very rapidly for unit changes in X when X is small, but rate of decrease of Y is much slower for changes in X when X is large (4:11).

In the equation $Y = AX^B$

Y = Cost per unit
A = Cost of the first unit produced
X = the unit number
B = log b/log 2
b = percent of learning (90% learning curve = .90) (5:528)

It is customary to represent the cost of the unit (Y) in terms of direct labor man-hours. Man-hours are normally used rather than dollar cost in order to eliminate an additional variable, the effect of inflation or deflation (wage-rate changes) (25:55). However, for this thesis dollar costs were used because the researchers were unable to obtain data on the direct labor man-hours required to produce turbine engines.

To compensate for the effect of inflation on turbine engine costs, all costs used in the learning curve computations for this thesis were adjusted to base year 1978 dollars. (See Appendix A for discussion on the use of price index numbers.)

There are two learning curve cost models. One model, called the "unit curve" or "Boeing" theory was validated by the Stanford Research Institute study (25:50). The unit curve model expresses cost as unit cost. The other learning curve model is the "Northrop" model, which bases cost on the cumulative average cost per unit (24).

In this thesis, cumulative average learning curve theory was used to compute the cumulative average cost of the validation engines.

Since the Navy's MF cost estimation models were based on the average cost of 1500 engines, the costs of the validation engines used in this thesis were adjusted to the cumulative average cost per unit of 1500 engines.

The following is a discussion of how the cumulative average cost of an engine based on the cumulative average cost of 1500 engines was determined. The percent of learning for a particular engine had to be determined. The Gray Book was used to determine (1) in what year a certain engine was produced, (2) the numbers of that engine produced in a year, and (3) the average cost of the engines in a

production run. Due to some reporting inconsistencies in the Gray Book, some approximations were necessary regarding the numbers of a particular engine produced in a year.

To compute the learning curve for an engine, at least two data points were required, that is, two different production runs for the same engine. All of the costs obtained for production runs were the selling price to the military adjusted to FY78 dollars.

The following is an example of the computations used to compute the percent of learning for a particular engine.

Production Year	Quantity Produced	Cumulative Quantity	Average Cost/Unit	1978 Average Cost/Unit
1962	831	831	\$169,400	\$344,309
1964	1190	2021	\$147,800	\$298,586

$$CAC_{\text{cum units}} = \frac{\text{QTY x Cost/Unit + QTY x Cost/Unit}}{\text{Cumulative Quantity}}$$

where

CAC = Cumulative Average Cost

QTY = Quantity

$$CAC_{2021} = \frac{831(344,309) + 1190(298,586)}{2021}$$

$$CAC_{2021} = \$317,387/\text{Unit}$$

The results of the computations shown above are tabulated in the following table.

Table 29

Cumulative Cost Summary

Cumulative Quantity	Cumulative Average Cost
831	$344,309
2021	$317,387

The figures in the above table were then used to compute the percent of learning for a particular engine. The equation

$$\hat{Y}_X = A(\frac{X}{K})^B$$

where

$\hat{Y}_X$ = Cumulative average cost per unit based on X units

A = Cumulative average cost per unit of K units

K = Some known production unit

X = Total cumulative units produced

B = log b/log 2

b = percent learning curve

was used (17).

The objective of the following computations was to determine b. Since all variables in the equation $\hat{Y}_X = A(\frac{X}{K})^B$ were known except B, the first step was to solve for B.

$$\hat{Y}_{2021} = A(\frac{X}{K})^B$$

From Table 29

$$\$317,387 = \$344,309\ (\frac{2021}{831})^B$$

$$(\frac{2021}{831})^B = \frac{\$317,387}{\$344,309}$$

$(2.432)^B = (0.9218)$

$\log(2.432)^B = \log(0.9218)$

$B \log(2.432) = \log(0.9218)$

$B = \frac{\log(0.9218)}{\log(2.432)}$

$B = -.0916$

The equation B = log b/log 2 was then used to find the percent of learning (b).

B = lob b/log 2

$\log b = B \log 2$

$\log b = -.0916 \log 2$

$\log b = -.0276$

$b = 10^{-.0276}$

$b = .938$

b = 94% learning curve

Thus, using two cost data points from the Gray Book, an approximate percent of learning of 94% for a particular engine was computed.

After the learning curve for a particular engine was determined, the cumulative average cost of an engine based on some constant number of engines produced could be calculated. This could be done regardless of the total number of engines of a particular type produced. As previously mentioned, all cost data were adjusted to a cumulative average cost based on 1500 engines. The following computations illustrate how the adjustment was accomplished.

$$\hat{Y} = AX^B$$

where

$\hat{Y}$ = Cumulative average cost/unit of first production run

A = Cost of first unit

X = Number of units

$B = \log b/\log 2$

From Table 29

$$\hat{Y}_{831} = \$344,309$$

$$X = 831$$

$$b = .94$$

$$B = \log .94/\log 2$$

$$B = -.089$$

Solve for A

$$\hat{Y}_{831} = AX^B$$

$$\$344,309 = A(831)^{-.089}$$

$$A = \frac{344,309}{(831)}{-.089}$$

$$A = \$626,315$$

To find the cumulative average cost based on 1500 engines,

$$\hat{Y}_{1500} = AX^B$$

$$\hat{Y} = \$626,315(1500)^{-.089}$$

$$\hat{Y} = \$326,679 \text{ (FY78 dollars)}$$

The computations shown were used on validation engines 6, 7, 8, and 9.

For validation engines 1, 2, 3, 4, and 5, the manufacturers' recommended percent of learning was used to adjust the engine costs to cumulative average costs. The

method of computing the cumulative average cost of engines 1, 2, 3, 4, and 5 varied for the different engines; therefore a brief explanation of the computation for each engine is given. Since the calculations for engine 1 were the most complex, this procedure is discussed first.

The standard method used to compute cumulative average cost per engine based on a cumulative average cost of 1500 engines was shown in the first part of this appendix. However, another method had to be used to compute the cumulative average cost for validation engine 1.

The proposed actual cost to the Air Force of a new advanced engine was obtained through the Propulsion Branch AFAPL. This engine was used as one of the validation engines for the different cost estimation models in this thesis. The cost was known for the total engine and was also broken down into the cost of the basic engine and the engine accessories. The proposed actual cost was based on the cumulative average cost per unit of the first 50 engines produced (17).

To make a valid comparison of validation engine actual cost to validation engine estimated cost using the various MF cost estimating models, the proposed actual cost of the validation engine had to be adjusted to the cumulative average cost per engine based on 1500 engines.

The manufacturer producing the validation engine believed that the cumulative learning curve behaves somewhat

differently than the Northrop learning curve. The manufacturer produced engines in lots of 50. They believed that cumulative average costs should be computed for each production lot of 50 engines, and this computation must be performed for each lot of 50 engines until the cumulative quantity of engines equals the desired cumulative basis of 1500 engines. However, the cumulative average cost per engine for the first 50 engines remains in the equation for all computations. The total cost for each lot was computed based on the cumulative average cost for each lot, and the summation of the computations was divided by 1500 to obtain the cumulative average cost per engine.

The equation $\bar{y}_x = A(\frac{X}{K})^B$ was used for the computations where

$\bar{y}_x$ = cumulative average cost per unit based on X units

A = known average cost of first production lot of 50 engines

X = cumulative quantity of engines (50 unit increments)

K = number of engines per production lot (K = 50)

B = log b/log 2 (Manufacturer uses 90% learning) (17)

Table 30

Cumulative Cost Computation of Validation Engine 1

Lot	Cumulative Quantity	Average Cost
50	50	(known) $526,000
50	100	.
50	150	.
.	.	.
.	.	.
.	.	.
50	1500	.

From Table 30, the following calculations were performed.

$$\bar{y}_x = A(\tfrac{X}{K})^B$$

$$B = \log .9/\log 2$$

$$B = -.152$$

$$\bar{y}_{50} = 526{,}000(\tfrac{50}{50})^{-.152}$$

$$\bar{y} = 526{,}000(1)$$

$$\bar{y}_{50} = 526{,}000$$

Total cost for production lot $(TC)_1 = 526{,}000 \times 50$

$$TC_1 = \$26{,}300{,}000$$

$$\bar{y}_{1500} = 526{,}000(\tfrac{1500}{50})^{-.152}$$

$$\bar{y}_{1500} = 526{,}000(.5963)$$

$$\bar{y}_{1500} = \$313{,}663$$

$$TC_{30} = 313,663 \times 50$$

$$TC_{30} = \$15,683,151$$

Using the same computations as shown above, the cumulative average cost based on 1500 engines can be found by using the equation

$$\bar{y}_{1500} = \frac{1}{1500}\sum_{i=1}^{30} TC_i$$

The calculations just shown were accomplished by computer using the program shown in Figure 6. The program was designed to compute the cumulative average cost per unit based on 1500 engines. The program can be used to determine:

1. the cost of the total engine (basic + controls)
2. the cost of the basic engine
3. the cost of the controls.

The standard learning curve computations discussed earlier were used to accomplish the cumulative average cost adjustment for validation engines 2, 3, and 4. However, engine 5 required a slight variation of the standard learning curve computation.

For validation engine 5, the manufacturer used two different percents of learning. The engine cost was separated into a basic cost and two different types of labor cost. The following computations were used to compute the cumulative average cost of engine 5.

$$\bar{Y}_{1500} = \text{Basic Cost} + A_1(X)^{B_1} + A_2(X)^{B_2}$$

where

```
C                              BARRETT/KOENIG
C
C THIS PROGRAM WILL COMPUTE THE CUMULATIVE AVERAGE COST OF 1500
C ENGINES USING THE CUMULATIVE AVERAGE COST OF THE FIRST 50 ENGINES.
C THE DATA USED IN THIS PROGRAM WAS OBTAINED FROM THE COMPANY
C MANUFACTURING OUR VALIDATION ENGINE.
C
C THE METHOD USED IN THIS PROGRAM TO COMPUTE THE CUMULATIVE
C AVERAGE COST IS THE TECHNIQUE USED BY THE VALIDATION ENGINE
C MANUFACTURER IN THEIR APPLICATION OF LEARNING CURVE THEORY
C
C A 90% LEARNING CURVE IS USED IN THIS PROGRAM
C
C                              LIST OF VARIABLES
C
C A = KNOWN AVERAGE COST OF FIRST PRODUCTION LOT OF 50 ENGINES
C X = CUMULATIVE # OF UNITS PRODUCED BASED ON 50 UNIT LOTS
C Y = CUMULATIVE AVERAGE COST FOR A PARTICULAR PRODUCTION LOT
C     OF 50 ENGINES USING 90% LEARNING CURVE
C YCOST = TOTAL COST OF A PARTICULAR LOT OF 50 ENGINES
C TOTCOST = SUMMATION OF TOTAL COST FOR EACH PRODUCTION LOT
C CUMAVG = CUMULATIVE AVERAGE COST OF 1500 ENGINES
C
  PRINT,"ENTER CUM AVG PRICE OF UNIT BASED ON FIRST 50 UNITS"
  READ,A
C INITIALIZE VARIABLES
  X=0
  Y=0
  TOTCOST=0
  YCOST=0
  CUMAVG=0
C COMPUTE CUM AVG COST FOR ONE ENGINE OF 50 UNIT LOT
  10 X=X+50.
  Y=A*((X/50.)**(-.152))
C COMPUTE COST OF 50 UNIT LOT
  YCOST=Y*50
  TOTCOST=TOTCOST+YCOST
  IF(X.LT.1500) GO TO 10
C COMPUTE CUM AVG COST OF 1500 ENGINES
  CUMAVG=TOTCOST/X
  PRINT 200,X,CUMAVG
  200 FORMAT(8X,F7.2,5X,F10.3)
  STOP
  END
```

Figure 6

CUMAVG Computer Program

```
40 CONTINUE
1000 FORMAT(V)
1010 FORMAT(2X,I6,2X,I4,2X,I4,2X,I4,2X,F6.2,2X,F4.2,2X,I1,2X,
& F6.3,2X,I6)
STOP
END
```

Figure 6 (continued)

$\bar{Y}_{1500}$ = cumulative average cost/unit based on 1500 engines

A_1 = labor cost of first engine

A_2 = labor cost of first engine

$B_i = \log b_i/\log 2$

b_i = percent of learning for different labor types

X = number of engines

$b_1 = .90$

$b_2 = .85$

$B_1 = \log .90/\log 2$

$B_1 = -.152$

$B_2 = \log .85/\log 2$

$B_2 = -.234$

$\bar{Y}_{1500} = 71{,}293 + 262{,}092(1500)^{-.152} + 55{,}416(1500)^{-.234}$

$\bar{Y}_{1500} = \$167{,}539$

APPENDIX C

MAURER FACTOR TECHNIQUE

The following is a step-by-step explanation of the procedure used to estimate the cost of validation engine 1 using the MF technique. The steps include engine component breakdown, materials classification, MF calculations, and determination of the final estimated cost.

Component Breakdown

Each individual component in the validation engine was identified, and the gross weight of the material used to make the component was determined. The component data are available on the DD Form 346s (Table 7) supplied by engine contractors. The component data for the validation engine were supplied by the engine manufacturer (Table 31).

Material Indexing

Using the Aerospace Material Specification (AMS) index, an AMS number was assigned to each material type (13:1-31).

MF Classification

The materials were classified using the seven MF categories (Table 32). The classification was accomplished by using the AMS conversion table shown in Table 33 and the data are shown in Table 34. The purpose of the MF categorization was to enable assignment of the MF weighting factor (f_i).

Table 31

Maurer Factor Computation Table
(Validation Engine 1)

Part	Gross Wt (lbs)	Alloy Name	MF Category[a]	Ratio (Gross Wt/ Finish Wt)
1	55.3	Titanium	T	1.7
2	65.4	Titanium	T	1.7
3	0.8	Aluminum	Conv	1.2
4	61.8	4340	Conv	3.6
5	14.0	Aluminum	Conv	2.3
6	19.4	Aluminum	Conv	2.3
7	4.8	Titanium	T	1.4
8	23.2	M50,440c	Conv	4.0
9	26.4	M50	Conv	4.0
10	72.8	Titanium	T	2.0
11	9.7	AMS6265	Conv	3.5
12	8.3	4340, M50	Conv	4.0
13	1.9	347	Conv	2.3
14	2.9	4340	Conv	1.4
15	6.0	Titanium	T	1.2
16	1.6	Aluminum	Conv	1.2
17	16.3	Inconel 718	C	1.4
18	67.7	Inconel 718	C	2.3
19	9.4	Inconel 718 Hastoloy X	C	2.3
20	15.5	Titanium	T	1.4
21	51.5	Inconel 718	C	1.4
22	18.0	HS 188	C	1.1
23	8.2	HS 188	C	1.4
24	75.2	HS 188	C	3.2
25	43.0	Inconel 718	C	3.3
26	38.5	Titanium	T	7.0

Table 31 (continued)

Part	Gross Wt (lbs)	Alloy Name	MF Category[a]	Ratio (Gross Wt/ Finish Wt)
27	171.0	Titanium	T	2.5
28	25.4	Inconel 718	C	6.5
29	149.6	Mar 247, Rene 95	D	1.7
30	15.9	Waspoloy, Inconel 718	C	6.5
31	13.4	M50	Conv	4.0
32	17.6	Inconel 718	C	5.9
33	57.8	Inconel 718	C	8.4
34	24.4	Waspoloy	D	2.3
35	13.7	Nickel, Waspoloy	D	3.3
36	11.0	HS25	C	2.3
37	28.3	Inconel 713LC	C	2.3
38	6.0	Inconel 718	C	1.2
39	48.9	Hastoloy X	C	1.7
40	12.1	Inconel 625	C	1.7
41	139.7	Inconel 713LC Waspoloy	D	1.7
42	98.8	Waspoloy	D	8.0
43	36.6	Inconel 625	C	7.0
44	22.5	Inconel 718, M50	C	4.0
45	63.1	4340	Conv	5.7
46	26.6	Hast X	B	4.4
47	22.5	Inconel 718, M50	C	4.0
48	29.6	Hast X	B	1.4
49	5.3	Titanium	T	1.2
50	7.6	Titanium	T	1.2
51	25.6	Hast X	B	1.2
52	25.3	Hast X	B	1.2
53	7.7	Titanium	T	1.2

Table 31 (continued)

Part	Gross Wt (lbs)	Alloy Name	MF Category[a]	Ratio (Gross Wt/ Finish Wt)
54	50.2	Hast X	B	50.2
55	12.0	Aluminum A357	Conv	2.0
56	2.4	Titanium	T	2.4
57	0.7	Inconel 718 C	C	1.4

Parts 58 thru 88 were engine accessories and were not included as part of the Maurer Factor conputation.

[a]See Table 32 for MF category symbology.

Table 32

Material Classification and Weighting Factors (18:99)

Material Classification	Percentage of Nickel + Cobalt	Weighting Factor
Conventional	0-24	1.00
A	25-44	6.65
Titanium (T)	-	10.50
B	45-59	13.95
C	60-69	24.00
D	70	29.75
E	>70	40.00

Table 33

Aerospace Material Specification (AMS)
Conversion Table

AMS	Classification	AMS	Classification
3004-4893	Conv	5554	A
4900-4966	T	5556-5566	Conv
4969-4973	T	5568	A
5000-5019	Conv	5570-5577	Conv
5020	T	5579-5580	A
5021-5341	Conv	5582	B
5342-5344	A	5585	B
5345-5353	Conv	5587	B
5354-5355	A	5589-5591	C
5358-5359	Conv	5596	C
5362	Conv	5597	A
5363	A	5599	C
5365-5366	Conv	5604	A
5368-5369	A	5610	Conv
5370-5372	Conv	5612-5613	Conv
5373	C	5616	A
5376	B	5620-5621	Conv
5380	C	5623	Conv
5382-5383	C	5624	A
5384	D	5625	Conv
5385	C	5627-5628	Conv
5387-5390	B	5630-5632	Conv
5391	C	5636-5637	Conv
5395	Conv	5639-5642	Conv
5396	B	5643-5644	A
5397	C	5645-5651	Conv
5398	A	5655	Conv
5504-5505	Conv	5656-5657	A
5508	A	5660-5661	B
5510-5519	Conv	5662-5663	C
5520	A	5664	C
5521-5524	Conv	5665	A
5525-5529	A	5666-5668	B
5530-5532	B	5669-5671	B
5536	B	5673	A
5537	C	5675	A
5540	A	5679	B
5541-5542	B	5680-5681	Conv
5543	A	5683	A
5544-5545	D	5685	Conv
5547-5549	A	5687	A
5550	B	5688-5691	Conv
5551	C	5694-5695	Conv
5552	A	5697	Conv

Table 33 (continued)

AMS	Classification	AMS	Classification
5698-5699	B	5798-5799	B
5707	D	5804-5805	A
5708	Conv	5812B	A
5709	D	5813B	A
5712-5713	D	5817	A
5720-5725	A	5821	Conv
5727-5729	A	5825-5827	A
5731-5737	A	5832	C
5738	Conv	6242	Conv
5741-5745	A	6250	Conv
5746	B	6260-6550	Conv
5750	B	7210-7211	Conv
5751	D	7222-7225	Conv
5753	D	7228-7229	Conv
5754	B	7232	A
5755	B	7233	Conv
5756-5757	C	7235	A
5759	C	7237	B
5768-5769	B	7240	Conv
5774-5775	A	7245	Conv
5776-5777	Conv	7278-7279	Conv
5778-5779	B	7304	Conv
5780-5781	A	7310-7312	Conv
5786-5787	B	7320	Conv
5794A	B	7322	Conv
5795B	B	7325	Conv
5796	C		

(18:101-102)

Table 34

Material Names By Classification

Conventional (weighting factor = 1.0--Nickel = 0-24%)	
15-5PH	AISI 8735-40
17-22A	B5F5
301-306	B1112
310, 316-321, 347	Chromology
403, 405, 410	D6ac
416, 420, 431, 440	M50
1010 Carbon Steel	Magnesium Thorium
1074, 1095	Nitrally N135
4130-4140	S Monel
4340	Wrought 4140, 464P
4640	Wrought Alloy Steel
8630	Vascojet 1000
9310	
A (weighting factor = 6.65--Nickel + Cobalt = 25-44%)	
15-7 PH	AM 355
17-4 PH	Greek Ascoloy
17-7 PH	Lapelloy
A286	Maraging Steel (18 Ni)
AM350	V57
B (weighting factor = 13.95--Ni + Co = 45-59%)	
D-979	Inconel 706, 901, W
Hastelloy B, C, N, X	Mar M247
Hastelloy W, R235	N-155
Incoloy T	S-590
Inconel 600, 601, 617	Stellite 6 (HS-6)
Inconel 700, 702, 750	
C (weighting factor = 24.0--Ni + Co = 60-69%)	
Hastelloy S	J-1570 & 1650
HS21, (X40) HS31	M-252
HS25 (L605)	M509
HS188	MAR M246, M302

Table 34 (continued)

C (weighting factor = 24.0--Ni + Co = 60-69%)	
Inconel 100, 102 Tube	S816
Inconel 625, 713, 718	Stellite 31
Inconel 722W, 738	V36
Inconel 792, 903, X	WI 152
D (weighting factor = 29.75--Ni + Co = 70%)	
Astroloy	U500
Rene 41, 63, 77	U700
Rene 80, 85, 95	Waspoloy
Rene 100, 120, 125	
E (weighting factor = 40.0--Ni + Co >70%)	
TD Ni	TD NiCr
T (weighting factor = 10.5--Titanium)	

MF Calculations

The MF calculation was accomplished by summing the product of the engine component gross weight and its MF weighting factor.

$$MF = \sum_{i=1}^{n} w_i \, f_i$$

where w_i is the gross weight of the component before machining and f_i is the MF weighting factor (Table 32).

The calculations in Table 35 were accomplished using the data in Table 31.

Table 35

Maurer Factor Calculation

MF Category	Gross Wt (in lbs)		MF Weighting Factor		
Conv	258.5	X	1	=	258.5
A	0	X	6.65	=	0
B	249.7	X	13.95	=	3935.62
C	572.1	X	24.0	=	13730.40
D	426.2	X	29.5	=	12572.90
E	0	X	40.0	=	0
T	452.3	X	10.5	=	4749.15
				MF =	35246.57

Final Estimated Cost

The CER of MF to engine cost was used to determine the estimated engine cost. For this report the following

cost estimating models developed by the Navy were used.

Model 1[1] CAMC = 4.453 (MF) + 3582

Model 2[1] CAMC = 1.875 (MF) + 48296

Model 3[1] CAMC = 1.669 (MF) + 73889

The MF calculated in Table 35 was used in Navy Models 1, 2, and 3 in an attempt to validate the MF technique. Using the calculated MF of 35246.57, the following results were obtained:

Model 1 CAMC = $160,535

Model 2 CAMC = $114,383

Model 3 CAMC = $132,716

Before the estimated costs obtained from Models 1, 2, and 3 could be compared to the actual cost of the validation engine, several adjustments had to be made.

First, the Navy models were based on manufacturing costs, so the profit and general and administrative (G&A) expenses included in the actual cost of the validation engine had to be removed. The manufacturer of the validation engine used a ten percent profit rate and a six percent G&A rate for the validation engine (17). The following computations were used to accomplish the profit and G&A adjustment:

Total Engine Cost	$524,947.10
Less Accessory Cost	100,571.43
Basic Engine Cost	$424,375.67

[1]CAMC represents the cumulative average manufacturing cost based on 1500 engines in FY65 dollars.

Remove Profit and G&A

Total Engine Cost	Engine Less Accessory	Accessory Cost
1.10 X = \$524947.10	1.10 X = \$424375.67	1.10 X = \$100571.43
X[2] = \$477224.64	X[2] = \$385796.06	X[2] = \$91428.57
1.06 Y = \$477224.64	1.06 Y = \$385796.06	1.06 Y = \$91428.57
Y[3] = \$450211.92	Y[3] = \$363958.55	Y[3] = \$86253.37

As discussed in Appendix B, the actual cost of the validation engine was based on the average cost of the first 50 engines produced; therefore, the validation engine's actual cost had to be adjusted to the cumulative average cost per unit based on 1500 engines. This adjustment was accomplished using the computer program CUMAVG shown in Figure 6, Appendix B.

Finally, all cost figures had to be adjusted to a common base year. For this report, FY78 was the base year (Appendix A).

---

[2] X represents cost with profit removed.

[3] Y represents basic cost with profit and G&A removed.

APPENDIX D

REGRESSION ANALYSIS

The main thrust of the analysis is to evaluate and measure the dependence of a variable on a set of independent variables. Within this thesis a dependent variable MF is regressed on independent variables, such as air flow (AF), maximum specific fuel consumption (MSFC), and afterburner (AB). Thus, a meaningful relationship of the dependent variable to independent variables will hopefully exist, enabling the prediction of turbine engine cost.

The dependent variable is plotted on the Y axis and the independent variables are plotted on the X axis. As depicted in Figure 1 the regression line is of the form

$$Y = \alpha + B_1 X_1 + e_1$$

where

Y = Estimated Maurer Factor

α = the constant added in each case

B = the constant coefficient by which the value of the independent variables is multiplied (regression coefficient)

X = the independent variables (turbine engine parameters)

e = the error in prediction, the residual (as depicted in Figure 7)

and is the best fitting line among the data points. The data points in this analysis are engine parameters and their associated Maurer Factor.

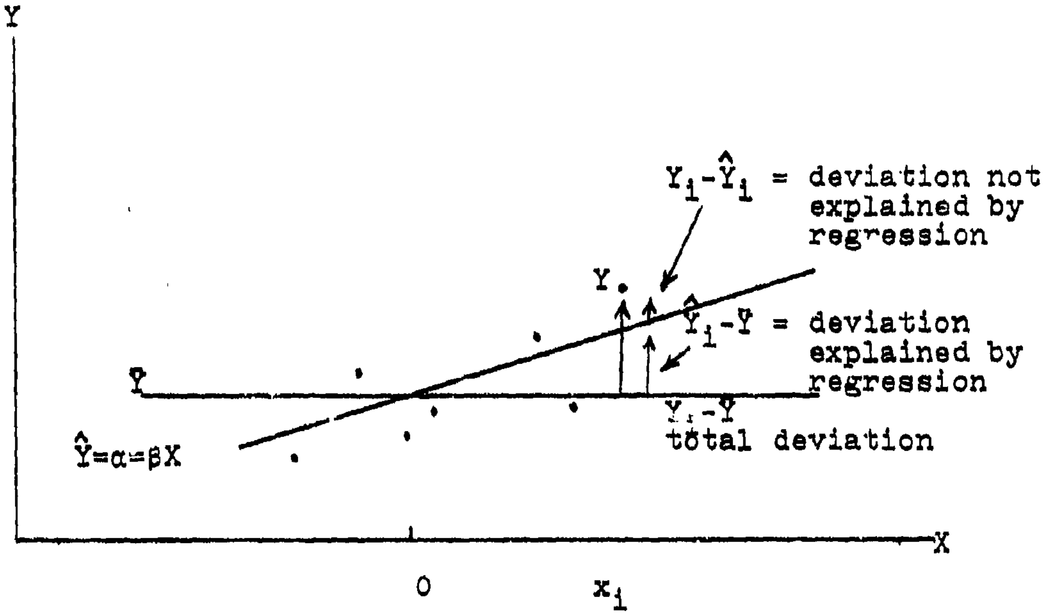


Figure 7

Graphic Representation of Deviation in a Regression Model (25:419)

In performing regression analysis, the following assumptions are made about the dependent and independent variables:

1. $E(e_i) = 0$; expected value of error.

2. $Var(e_i) = \alpha^2$; variance of error.

3. The e_i's are normally distributed.

4. The e_i's are independent.

5. The number of observations (n) is greater than the number of parameters in the model.

6. The rank of the X matrix is P (the number of parameters).

   a. Each column of data in the matrix must be linearly independent.

   b. If not linearly independent, the matrix cannot be inverted.

7. The independent variables are observed without error (25:341).

For a model to be considered valid, the assumptions should be met. The verification of these assumptions is explained by the use of statistical tests on the model.

The method used to estimate the linear regression is the least squares method. Model 4 is the predictor model in this case and is of the form

$$EMF = -58966.135 + 311.468\ (AF) + 67321.157\ (MSFC) -56753.280\ (AB)$$

where

EMF = The estimated Maurer Factor

AF = Air Flow

MSFC = Maximum specific fuel consumption

AB = Afterburner

and to validate the model, the F-test and t-test were conducted. The predictor model was achieved using a computer multiple regression subprogram. (See Figure 8 for the Model 4 statistical program.) This subprogram also provided the statistics for the F-test and t-test (Table 36).

F-test

An F-test is performed to determine if a statistically significant relationship exists between the dependent variable and the independent variables. In Model 4 the F ratio,

$$F = \frac{\text{variance explained by regression}}{\text{unexplained variance}},$$

is equal to 17.98. To determine whether the model is significant the F ratio is compared to a critical F (F_c) calculated using an F Statistics Distribution Table (25:716-717). If $F \leq F_c$ then the null hypothesis (H_o) cannot be rejected.

$$H_o : \beta_1 = \beta_2 = \ldots = \beta_{p-1} = 0$$

However, if $F > F_c$ then H_o can be rejected and further testing of the model can be continued. In Model 4, $F = 17.98 > F_c = 3.32$ which is significant, thus reject H_o.

```
ØØ1Ø##S,J ;,8,16;;,16
ØØ2Ø$:IDENT:WP1189,AFIT/LSC KOENIG/BARRETT STUDENTS 79A
ØØ3Ø$:SELECT:SPSS/SPSSNMSG
ØØ4ØRUN NAME;THESIS EST MAURER FACTOR MLR MF ON ENG PARAMETERS
ØØ5ØVARIABLE LIST;MF,WT,AF,TIT,DIA,TW,AB,MSFC,MTRST
ØØ6ØINPUT FORMAT;FREEFIELD
ØØ7ØINPUT MEDIUM;CARD
ØØ8ØN OF CASES;35
ØØ9ØIF;(AB EQ Ø) ABØ=1
Ø1ØØIF;(AB EQ 1) AB1=1
Ø11ØREGRESSION;VARIABLES=MF,AF,TIT,ABØ,AB1/
Ø12Ø;REGRESSION=MF WITH AF,TIT,AB1(1) RESID=Ø
Ø13ØSTATISTICS;1,2,4,5,6
Ø14ØREAD INPUT DATA
Ø15Ø#:SELECTA:79A62/MFDATA2
Ø22ØFINISH
Ø23Ø$:END JOB
```

Figure 8

Multiple Regression Computer Program

Table 36

Regression Table Generated by SPSS
Subprogram REGRESSION (21:331)

Multiple R	Ø.79686	Analysis of Variance	<u>DF</u>	<u>SS</u>	<u>F</u>
R^2 Square	Ø.63498	Regression	3	Ø.17Ø77E12	
Standard error	56272.65Ø71	Residual	31	Ø.98165E11	17.9757Ø

Variable	β	B	Standard error β	F
AF	311.46783	Ø.86831	42.42471	53.9ØØ
MSFC	67321.1572Ø	Ø.6246Ø	284Ø4.92357	5.617
ABI	-56753.27938	-Ø.32253	4471Ø.965Ø4	1.611
(constant)	-58966.1354Ø			

t-test

In Model 4 above, the null hypothesis for the overall model was rejected; therefore, at least one of the regressors (independent variables) in the model was significant. To check the regressor for significance, a t-test was performed on each of the independent variable's coefficient, the hypothesis being $H_0 : \beta = 0$.

The information was again obtained from Table 36. The t value associated with each of the independent variables is equal to the square root of that variable's F statistic, thus:

$$t_{AF} = \sqrt{53.9} = 7.34$$

$$t_{MSFC} = \sqrt{5.617} = 2.37$$

$$t_{AB} = \sqrt{1.611} = 1.27$$

Again, the critical t (t_c) was taken from the Student's t Critical Points table (25:713). Since $t_c = 2.042$, and t_{AF} and $t_{MSFC} > t_c$, air flow and maximum specific fuel consumption are significant variables in the model. Afterburner does not prove significant, but the variable may still add to the model. In Model 4, afterburner was included (25:345-346).

Thus far, the F test of the overall model indicated a good model; and the t tests of the individual regressors implied that AF and MSFC were significant regressors. However, further testing must be accomplished to indicate whether there exists a relationship among the residuals

called autocorrelation. A relationship occurs most often in time series data or when an important variable is left out of the model. From the multiple regression subprogram, a Durbin-Watson statistic is produced which is used to detect autocorrelation. (See Table 37 for the Durbin-Watson statistic.)

The Durbin-Watson test uses two limiting values of a critical D (Durbin-Watson statistic)--D_L and D_U which correspond to a lower and upper D. In this test two hypothesis exist,

H_o: No positive autocorrelation

H_a: Positive autocorrelation

and

H_o: No negative autocorrelation

H_a: Negative autocorrelation

D in Table 37 for Model 4 equals .63. This value is then used in the Durbin-Watson test for autocorrelation (29:721). Using a Durbin-Watson Table,

$n = 35$

$K = 3$

$D_L = 1.275$

$D_U = 1.655$

$D = .63$

therefore,

$D < D_L$

hence, positive autocorrelation exists. A test for negative autocorrelation is therefore unnecessary (25:720-721).

Table 37

Durbin-Watson Statistic (21:352)

Durbin-Watson Test of Residual Differences Compared by Case Order (SEQNUM).

Variable List 1, Regression List 1. Durbin-Watson Test Ø.63

```
PARAMETER N=35
DIMENSION INF(35),INT(35),IAF(35),ITIT(35),DIA(35)
DIMENSION TW(35),IAB(35),FC(35),INTUST(35)
CALL ATTACH(11,"79A62/EMFDATA2;",1,0,,)
CALL ATTACH(12,"79A62/EMFDATA4;",3,0,,)
DO 10 I=1,N
READ(11,1000)LN,INF(I),INT(I),IAF(I),ITIT(I),DIA(I),TW(I),IAB(I),
& FC(I),INTUST(I)
10 CONTINUE
DO 20 I=1,N-1
J=I
DO 30 J=J+1,N
IF(ITIT(I).LE.ITIT(J)) GO TO 30
IT=INF(I)
INF(I)=INF(J)
INF(J)=IT
ITE=INT(I)
INT(I)=INT(J)
INT(J)=ITE
ITEM=IAF(I)
IAF(I)=IAF(J)
IAF(J)=ITEM
ITEMS=ITIT(I)
ITIT(I)=ITIT(J)
ITIT(J)=ITEMS
TE=DIA(I)
DIA(I)=DIA(J)
DIA(J)=TE
TEM=TW(I)
TW(I)=TW(J)
TW(J)=TEM
ITEMP=IAB(I)
IAB(I)=IAB(J)
IAB(J)=ITEMP
TEMP=FC(I)
FC(I)=FC(J)
FC(J)=TEMP
ITEMPS=INTUST(I)
INTUST(I)=INTUST(J)
INTUST(J)=ITEMPS
30 CONTINUE
20 CONTINUE
DO 40 I=1,N
WRITE(12,1010)INF(I),INT(I),IAF(I),ITIT(I),DIA(I),TW(I),IAB(I),
& FC(I),INTUST(I)
```

Figure 9

Program for Ordering Data

The findings of positive autocorrelation in Model 4 indicate that it would not be a reliable predictor of values for MFs.

APPENDIX E

PROFIT AND G&A COST ADJUSTMENT

The dollar amounts for the validation engines used were the selling price of the engines to DOD. Since the Navy Maurer Factor cost models were based on manufacturing cost, the prices for the validation engines had to be adjusted to manufacturing costs. This adjustment was accomplished by removing profit and general and administrative (G&A) costs from the engine prices. The profit and G&A rates were calculated by a cost analyst in the Propulsion Branch. Calculations were based on available pricing information for the engines under consideration. Table 38 is a summary of the rates used.

Table 38

Profit/G&A Rates

Validation Engine Number	Profit/G&A Rate (%)
1	16
2	46
3	25
4	25
5	38.8
6, 7, 8, 9	16

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ABBREVIATIONS AND ACRONYMS

AB	Afterburner, dummy variable to indicate the presence of an afterburner
AF	Air Flow, maximum rated for an engine
AFAPL	Air Force Aero Propulsion Laboratory
AMS	Aerospace Material Specification
CAMC	Cumulative Average Manufacturing Cost
CER	Cost Estimating Relationship
CI	Confidence Interval
DOD	Department of Defense
DTT	Delta Technology Time
EMF	Estimated Maurer Factor
EPR	Engine Pressure Ratio
FY	Fiscal Year
GESP	General Electric Specification
MACH	Sea Level Limiting Mach
MF	Maurer Factor
MTRST	Maximum Thrust
MQT	Model Qualification Test
MQTYR	Model Qualification Test Year
PRESS	Overall Pressure Ratio
RPM	Revolution Per Minute
RPMMAX	RPM of an engine at Maximum Thrust
SFC	Specific Fuel Consumption
MSFC	SFC at Maximum Power
TIT	Turbine Inlet Temperature
TOA	Time of Arrival